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Generic Extruded Propellant Grain Surface and Volume Calculations

by Ronald D. Anderson

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14. ABSTRACT

Experimental propelling charges that have non-standard extruded granular shapes require calculations of available burning surface area in order to be simulated by interior ballistic (IB) modeling applications. Formerly, extensive hand calculations or development of a one-of-a-kind form function was necessary in order to analyze the changes in surface area whenever non-standard grain geometries were to be used in experimental gun propelling charges. A quick, easy-to-use computer program has been developed to calculate surface and volume of propellant grains versus depth burning by an analysis of propellant slivers; the results are then added to create a full-grain form function. The resultant data can be used in IB programs to estimate maximum pressures and projectile velocities from experimental propelling charges and gun systems.

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1. Introduction

Simulation of experimental interior ballistic phenomena often relies upon an approximation of burning propellant surface area to be used in one or more interior ballistic (IB) programs for the calculation of expected pressures and projectile velocities. If the experimental propellant uses a well-known physical granulation (single-, 7-, or 19-perforated cylindrical grains), then calculations with existing form functions in interior ballistic programs such as IBHVG2[1] (*1*) or XNOVAKTC[2] (*2*) can supply the needed surface area to estimate burned propellant volume (area of burning surface multiplied by depth burned at a given pressure during a time step). With an estimate of volume burned, known (or estimated) IB thermodynamic values, and physical chamber dimensions, a computation of pressure rise can be made for the gun chamber. The calculated pressure can then be used in the next time step to predict the volume of propellant to be burned. By repeating this series of calculations through a number of time steps, we can estimate the history of the propellant burn.

If the burned propellant volume from one step to the next is not known because of lack of a form function to estimate current burning surface area, the two noted IB programs may still be used if an array of values for surface area versus depth burned can be calculated. In experimental ballistics, this is not always straightforward because of the occasional use of non-traditional grain geometries. Extruded grains of outer geometry other than circular, hexagonal, or rosette cause problems in simulation because computation of surface area is difficult. Labor-intensive hand calculations are not always an option for time-sensitive experimental ballistic experiments.

This report describes the analysis used to develop algorithms to calculate surface area and volume versus depth burned for generic grain slivers. These algorithms are used to simulate IB form functions of non-traditional extruded grains. The report also describes the use of a program based on the algorithms.

2. Analysis of Simulation Process

The sliver-adding process for granular surface and volume computations is demonstrated by the example of a hexagonal 19-perforation grain. The end surface of such a grain is shown in figure 1. If one draws lines between perforations, the central portion of the grain end can be divided into 24 equilateral triangles with perforation centers at each vertex. The three-dimensional (3-D) triangular sections are termed “slivers.” The outer portion of the grain can be viewed as 12 rectan-

[1]IBHVG2 = interior ballistics of high velocity Guns, Version 2.
[2]XNOVAKTC = extended Nova with kinetic tank charge.

gular slivers, with a perforation center at each interior corner. (Hereafter, the description "outer" will always refer to a section or edge along the lateral surface of the grain, where the "end" and "side" edges meet.) The remaining end area consists of six outer vertices with circular single-perforation slivers of 60-degree arc at each vertex.

By computing the end area of each sliver type, multiplying by the number of slivers, and multiplying again by grain length, we obtain the total volume of propellant in a grain. Total surface area is end area doubled, plus the sum of perforation arc lengths and outer edge lengths (exterior edges of each rectangular section plus the outer curves of the six outer vertices) multiplied by grain length. As the grain burns, the perforations become bigger, the depth of each rectangular sliver becomes smaller, and grain length is reduced. When burn-through occurs (perforation-to-perforation intersection and/or outer perforation-to-exterior edge intersection), the surface area rapidly decreases because of the reduction in burning perforation arc lengths.

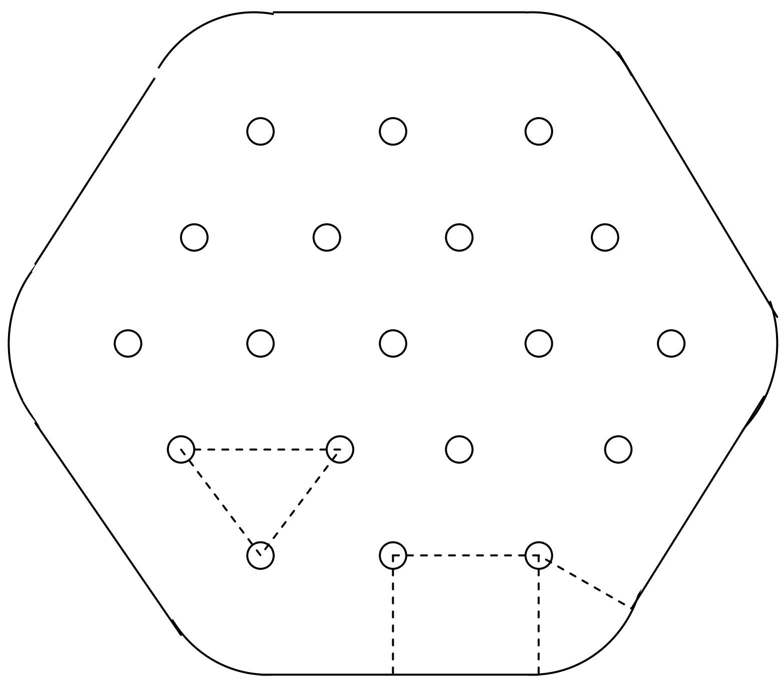


Figure 1. Nineteen-perforation hexagonal grain end.

3. Experimental Grain Geometry

One of the recent developments in propellant grain geometry is a multi-perforated grain designed to fit between the fins of a kinetic energy (KE) long-rod penetrator projectile as it is loaded into a cartridge case. An end geometry of such a grain is drawn in figure 2. Calculating grain surface area and volume requires looking at the total grain as a series of smaller lengthwise sections.

The perforations are arranged in a pattern similar to those in a standard 7- or 19-perforation cylindrical grain and can be viewed as equilateral triangular propellant slivers. Outer edge slivers can be divided into trapezoidal sections along the lower and lower side edges, with a section of circular single-perforation sliver at the lower corner.

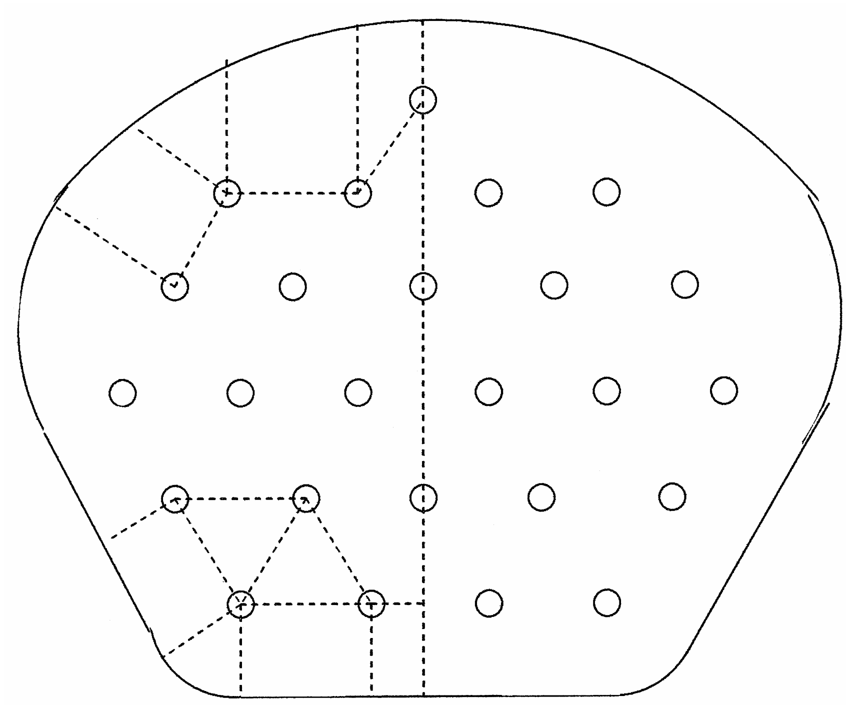
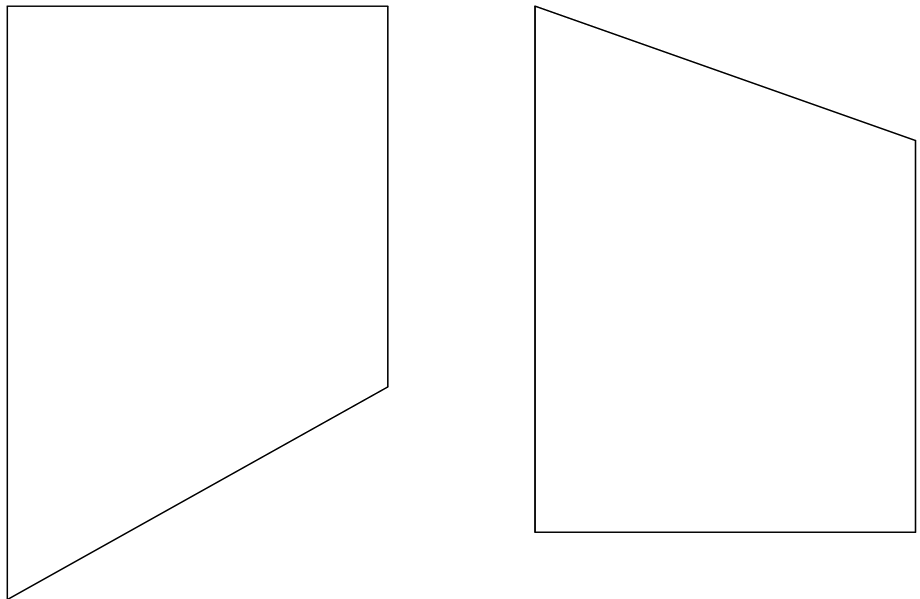


Figure 2. Twenty-five-perforation extruded grain end.

Upper side and top edge sections are less "regular" than the previous slivers since the outer edges are arcs of radius much larger than the lower corner. These slivers may be approximated with trapezoidal sections where side lengths are equal to the computed depth of interior perforation centers. Since the grain is mirrored along the vertical line shown in figure 2, only one side needs to be modeled, and then the results are doubled for final values of volume and burning area.

4. Trapezoidal Slivers

Calculation of trapezoidal sliver end area and burning edge will be done in two ways: type 1 trapezoid will require the outer (burning) edge to be perpendicular to the sides (figure 3(a) with outer edge topmost); type 2 trapezoid shown in figure 3(b) will require the line connecting the centers of perforations (bottom corners) to be perpendicular to the sides. Either method will suffice for the calculation of a rectangular sliver that conforms to both requirements.



(a) type 1 (b) type 2

Figure 3. Type 1 and type 2 trapezoids.

4.1 Type 1 Trapezoidal

Figure 4 shows a sliver with no perforations at the inner corners where point **E** is positioned so that **AE** = **CD**. Line **AD** in figure 4 corresponds to the outer burning edge of the propellant grain, and line **AD** is perpendicular to lines **AB** and **CD**. Line **A'D'** would be the position of the burning edge when the burned depth is distance **AA'**. The nominal end area of the sliver is width (**AD**) times one-half the sum of the parallel sides (**A'B** and **CD'**), or

$$\mathbf{END = 0.5 * AD * (A'B + CD')},$$

unless the outer edge has burned past point **E** (figure 5). When **A'B < BE** the nominal end area is

$$\mathbf{END = 0.5 * AD * BE}$$

with a reduction of end area equal to

$$\mathbf{ENDR = 0.5 * A'E * (AD + A'D'))}$$

in which

$$\mathbf{A'E = BE - A'B}$$

and

$$\mathbf{A'D' = AD * A'B / BE}.$$

The length of the burning outer edge is **AD** unless the edge has burned past the end of the shorter side as in figure 5; then the burning edge is reduced to **A'D'**. The equations for nominal end area (**END**) will be used for all the following type 1 and type 2 trapezoidal sliver analyses.

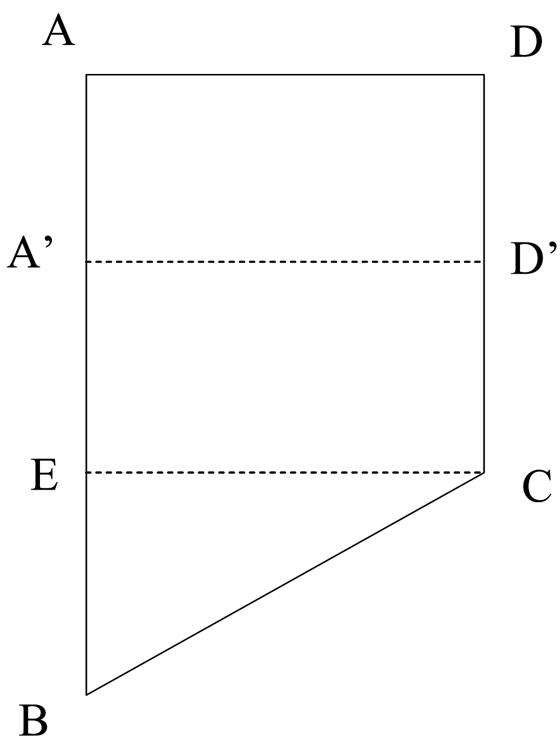


Figure 4. Type 1 0-perforation partially burned trapezoid.

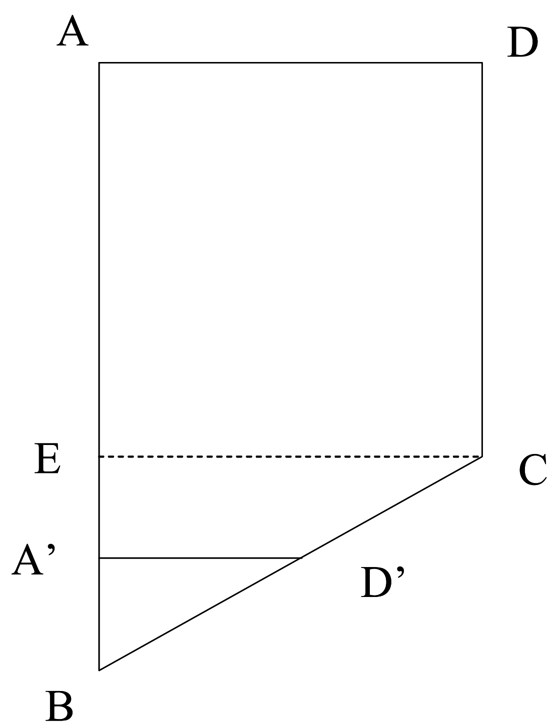


Figure 5. Type 1 trapezoid – no perforation, burned depth greater than short side.

4.1.1 Single Perforation on Short Side

If the trapezoid contains a perforation centered at the end of the shorter edge (figure 6), while **CG < AD** and **CG < CD'**, nominal end area is reduced by

$$\mathbf{ENDL = 0.5 * ARCS * CG * CG}$$

in which **CG** is the perforation radius, **BC** is defined as

$$\mathbf{BC = Sqrt\ (AD*AD + [AB - CD] * [AB - CD]),}$$

and

$$\mathbf{ARCS = PI / 2 + Cos^{-1}(AD / BC)}$$

is measured in radians. Burning outer edge length is **AD** and burning perforation arc length is

$$\mathbf{BPE = ARCS * CG}.$$

When **A'B > BE**, **CG < AD**, and the burning outer edge intersects the perforation (figure 7) at a point **F** where **A'E < CG**, **ARCS** becomes

$$\mathbf{ARCS = PI / 2 + Cos^{-1}(AD / BC) – Cos^{-1}(CD' / CG),}$$

and end area of the trapezoid (nominally **0.5 * (AD * (A'B + CD'))**) is reduced by

$$\mathbf{ENDS = 0.5 * CD' * FD' + 0.5 * CG * CG * ARCS}$$

in which

$$FD' = Sqrt(CG * CG - CD' * CD').$$

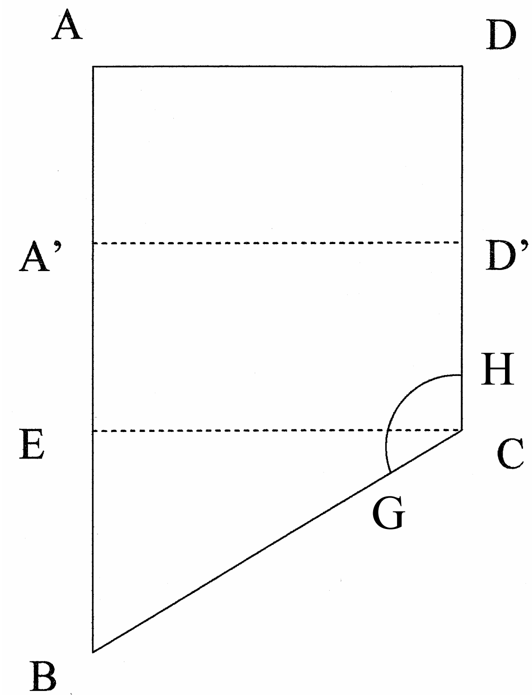


Figure 6. Type 1 short-side single-perforation trapezoid – partially burned, no intersection with perforation.

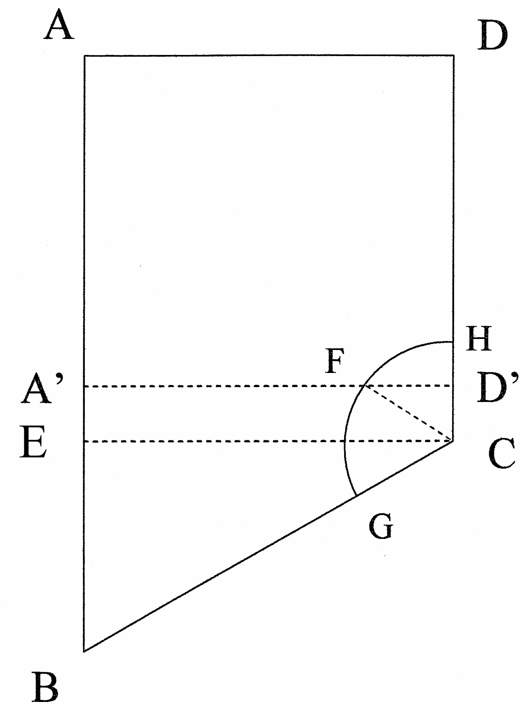


Figure 7. Type 1 SS SP – burn intersection with perforation arc.

Burning outer edge length is simply **AD – FD'** and burning perforation edge is

$$BPE = ARCS * CG.$$

If **A'B < BE** and **A'B > CG * BE / BC** (figure 8), nominal end area **0.5 * BE * AD** is reduced by

$$ENDS = 0.5 * A'E * (A'F + AD) + 0.5 * CG * CG * ARCS$$

in which

$$A'F = AD - Sqrt(CG * CG - A'E * A'E)$$

and

$$ARCS = Cos^{-1}(AD / BC) - Sin^{-1}(A'E / CG).$$

Burning perforation edge is **ARCS * CG**, and burning outer edge length is **A'F**.

If **A'E < CG * BE / BC** (figure 9), then revert to figure 5 and the perforation has no bearing on end area or burning edge.

When **CG > AD** and **A'B > BE + CG** (figure 10), the total burning perforation arc is

$$ARCS = PI / 2 + Cos^{-1}(AD / BC) - 2 * Cos^{-1}(AD / CG)$$

and burning perforation edge is

$$\mathbf{BPE = ARCS * CG}.$$

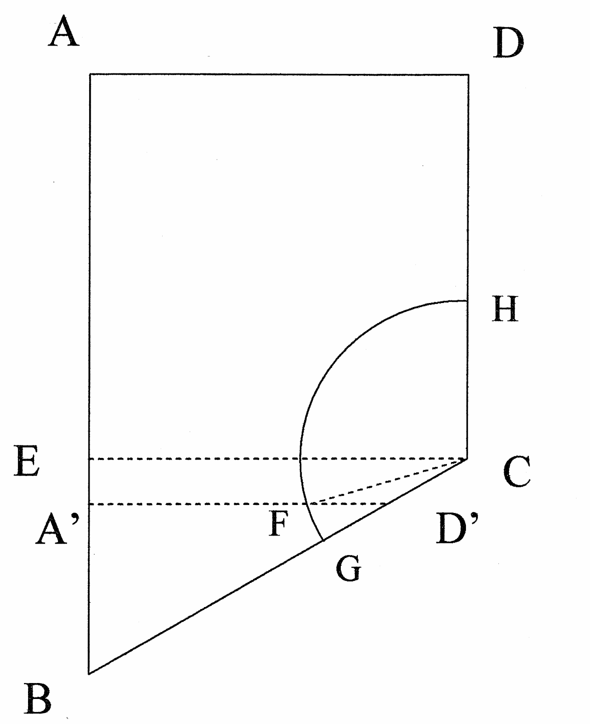


Figure 8. Type 1 SS SP – burn depth greater than short side, intersection with perforation arc.

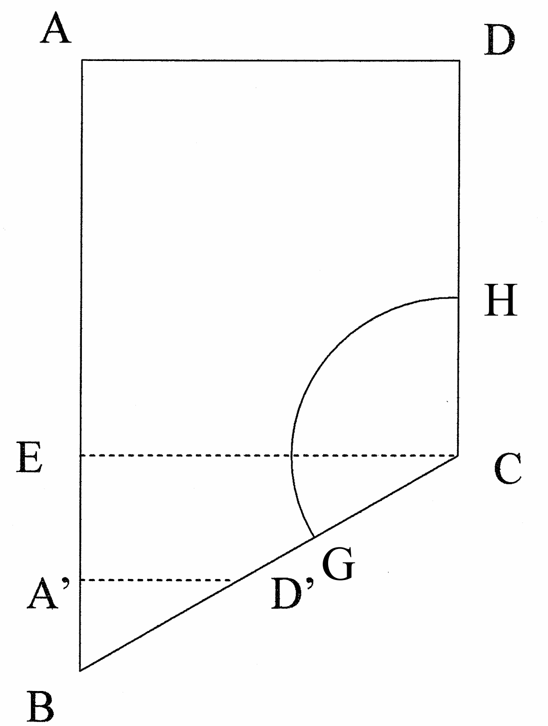


Figure 9. Type 1 SS SP – burn depth greater than perforation arc.

Burning outer edge is **AD**, and end area is calculated as in figure 4 reduced by

$$\mathbf{ENDS = AD * EK + 0.5 * CG * CG * ARCS}$$

in which

$$\mathbf{EK = Sqrt(CG * CG - AD * AD)}.$$

If **CG > AD** and **EK < A'E < CG** (figure 11), burning perforation arc is

$$\mathbf{ARCS = PI / 2 + Cos^{-1}(AD / BC) - 2 * Cos^{-1}(CE / CG) - Cos^{-1}(CD' / CG)},$$

making the burning perforation edge length **ARCS * CG**. Burning outer edge is **AD – Sqrt(CG * CG – CD' * CD')**, and end area reduction is

$$\mathbf{ENDS = AD * EK + 0.5 * (CG * CG * ARCS - CD' * FD')},$$

in which

$$\mathbf{FD' = Sqrt(CG * CG - CD' * CD')}.$$

When **CG > AD** and **A'E < EK** (figure 12), the burning outer edge is non-existent. The burning perforation edge arc is

$$\mathbf{ARCS = Cos^{-1}(AD / BC) - Cos^{-1}(AD / CG)}.$$

Burning perforation edge length is **CG * ARCS**, and the end reduction is calculated as

$$\mathbf{ENDS = 0.5 * (AD * EK - CG * BPE)}.$$

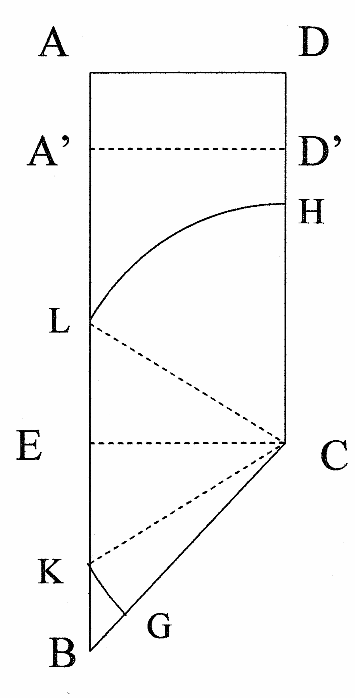


Figure 10. Type 1 SS SP – perforation arc greater than width, no burn intersection.

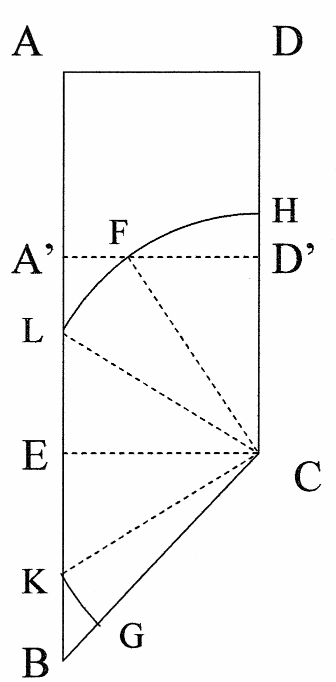


Figure 11. Type 1 SS SP – perforation arc greater than width, intersection with burn.

If **CG > AD**, **A'B < BE**, and **A'E > EK** (figure 13), then the computation reverts to the same equations as for figure 8.

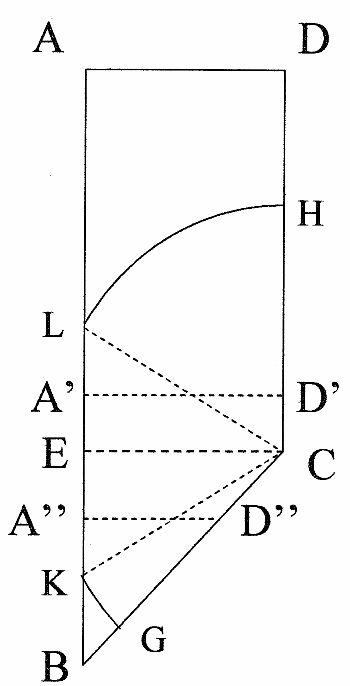


Figure 12. Type 1 SS SP – perforation arc greater than width, burn within perforation void.

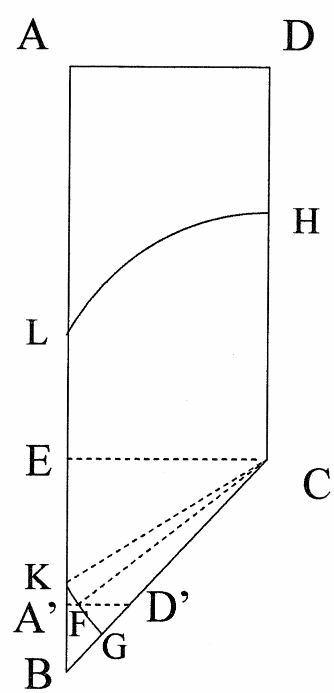


Figure 13. Type 1 SS SP – perforation arc greater than width, burn intersection with lower perforation arc.

When the burning outer edge burns past the short-side perforation (unlikely, but supported here), as in figure 14, it is characterized by **A'B < BE** and **A'B < BE * (BC – CG) / BC**. In this case, revert to the calculations for figure 5.

If the short-side perforation should burn to a radius greater than the distance between inner corners, or **CH > BC**, and **CD' > CH** (figure 15), then the burning outer edge is of length **AD**, burning perforation arc length is **CH * ARCS** where

$$\mathbf{ARCS = PI / 2 - Cos^{-1}(AD / CH)},$$

and end area reduction is

$$\mathbf{ENDS = 0.5 * (AD * EL + CH * CH * ARCS + AD * BE)}$$

in which

$$\mathbf{EL = Sqrt(CH * CH – AD * AD)}.$$

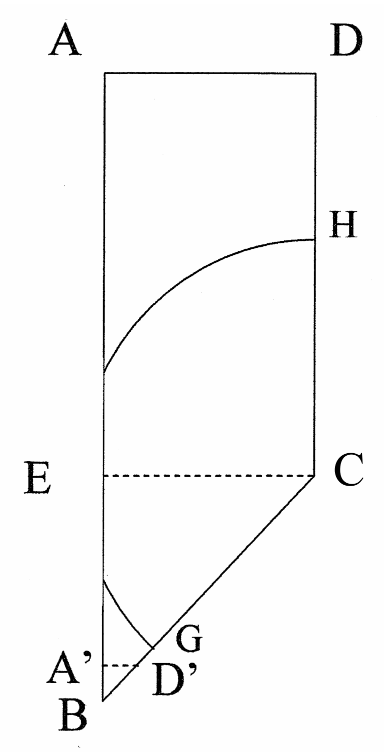


Figure 14. Type 1 SS SP – burn beyond perforation arc.

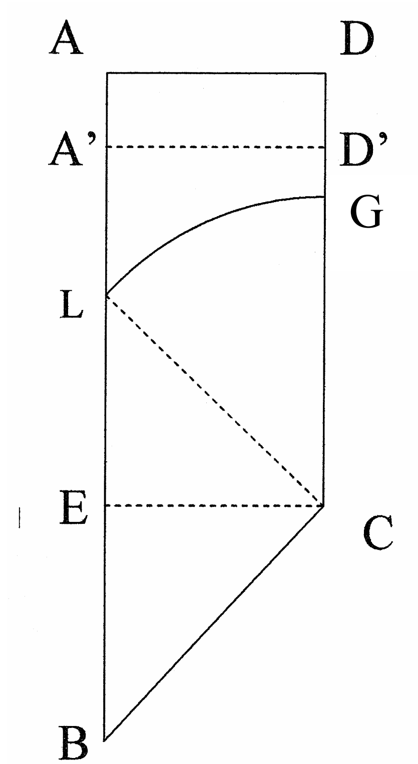


Figure 15. Type 1 SS SP – perf arc greater than inner corner distance, no burn intersection with arc.

When **CG > BC** and the outer edge intersects burning perforation edge as in figure 16 (**A'E < CG** and **A'E > Sqrt(CG * CG – AD * AD)**), then

$$\mathbf{ARCS = (PI / 2 - Cos^{-1}(AD / CG) - Cos^{-1}(CD' / CG))}.$$

Burning perforation edge **BPE** is **CG * ARCS**. Burning outer edge is

$$\mathbf{BOE = AD – Sqrt(CG * CG – CD' * CD')},$$

and end area is reduced by

ENDS = 0.5 *(AD * (BE + EL) + CD’ * (AD – BOE) + CG * BPE)

where **EL** is defined as for figure 15.

If **CG > BC** and **A’E < Sqrt(CG * CG – AD * AD)** (figure 17), then the sliver has burned out and no further calculations are necessary.

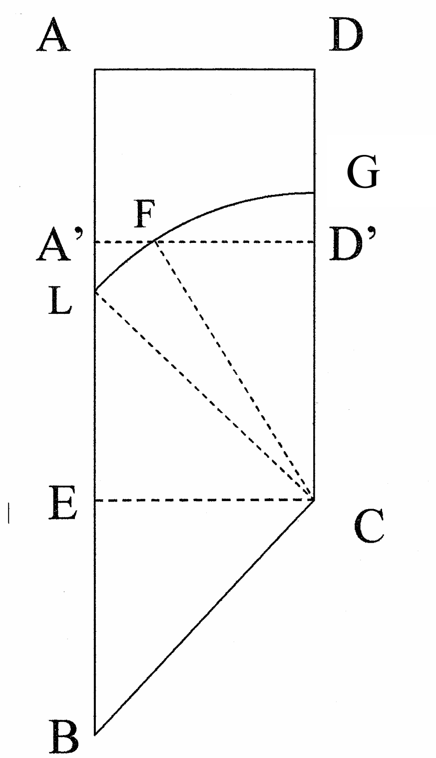


Figure 16. Type 1 SS SP – perf arc greater than inner corner distance, burn intersection with arc.

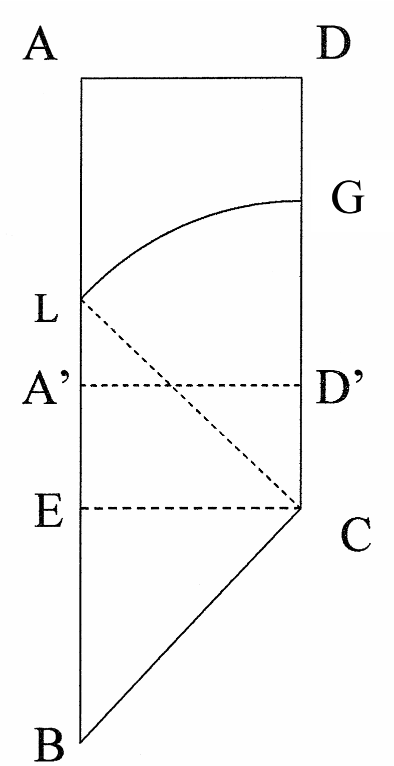


Figure 17. Type 1 SS SP – burned out.

4.1.2 Single Perforation on Long Side

In figure 18, the trapezoid has a single perforation of radius **BQ** centered at the inner end of the long side. Let **A’D’** be the current burning outer edge. When **BQ < BC**, **A’B > BE**, and **A’B > BQ**, then **AD** is the length of the burning outer edge, end area is reduced by

$$\mathbf{ENDL = 0.5 * BQ * BQ * Cos^{-1}(BE / BC)},$$

and burning perforation arc length is

$$\mathbf{BPE = BQ * Cos^{-1}(BE / BC)}.$$

When **A’’D’’** is the burning outer edge, **A’’B > BP** and **A’’B < BE**, then the length of the burning perforation edge is the same as in the latter case, but burning outer edge is

$$BOE = A''B * AD / BE.$$

The reduced area is the same as in figure 5 except for the perforation on the long side; its area reduction is the following:

$$ENDL = 0.5 * BQ * BQ * \cos^{-1}(BE / BC).$$

Let $BV = BQ * BE / BC$. When $A'''D'''$ is the current burning outer edge and $A'''B < BV$, then the sliver has burned out; end area and burning edge lengths are all equal to zero.

In figure 19, current burning outer edge $A'D'$ has progressed so that $A'B < BE$, $A'B < BP$ and $A'B > BV$, then

$$BOE = A'D' – A'T,$$

in which

$$A'T = AD – \mathrm{Sqrt}(BQ * BQ – A'B * A'B),$$

and

$$A'D' = AD * A'B / BE.$$

In this case, burning perforation edge is

$$BPE = BQ * (\cos^{-1}(BE / BC) - \cos^{-1}(A'B / BQ)),$$

and nominal end area is reduced by

$$ENDL = 0.5 * ((A'D' + AD) * A'E – (A'T * A'B) – BQ * BPE).$$

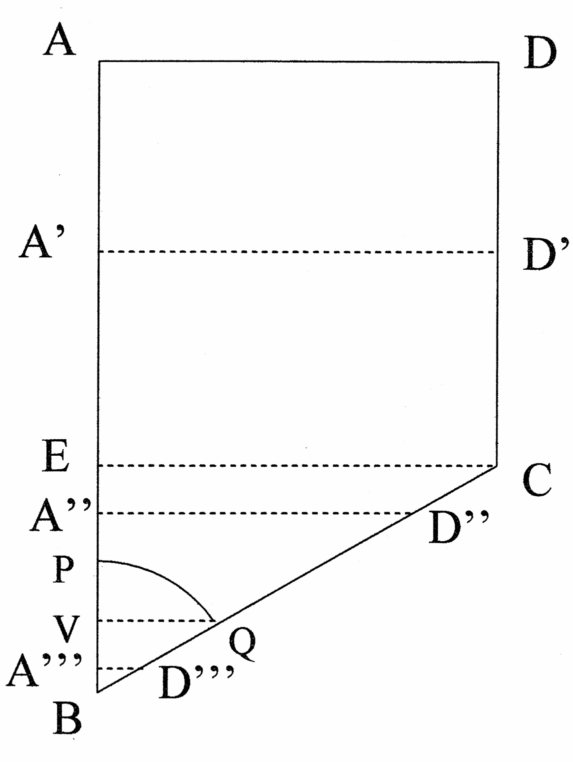


Figure 18. Type 1 long-side single-perforation trapezoid – no perforation arc intersection.

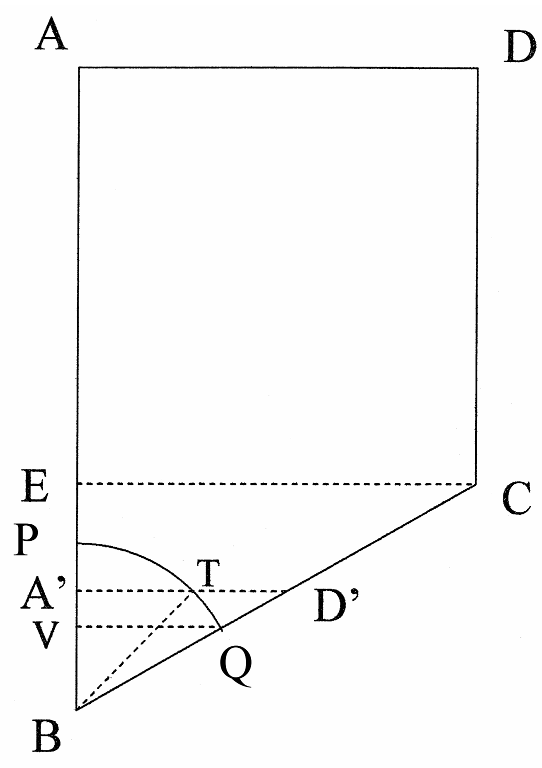


Figure 19. Type 1 LS SP – burning surface intersection, radius less than diagonal.

When **BQ > BC** and **A'B > BQ** as in figure 20, then burning outer edge length is **AD**, burning perforation edge is

$$\mathbf{BPE = BQ * Sin^{-1}(AD / BQ)},$$

and end area reduction is

$$\mathbf{ENDL = 0.5 * (AD * CQ + BQ * BPE)},$$

in which

$$\mathbf{CQ = Sqrt(BQ * BQ - AD * AD) - BE}.$$

In figure 21, where the burning outer edge intersects the perforation arc, **BQ > A'B > BV** where

$$\mathbf{BV = Sqrt(BQ * BQ - AD * AD)}.$$

Then burning perforation edge is reduced to

$$\mathbf{BPE = BQ * (Sin^{-1}(AD / BQ) - Sin^{-1}(A'T / BQ))}.$$

Burning outer edge length is now

$$\mathbf{BOE = AD - A'T},$$

and the grain end area is reduced by

$$\mathbf{ENDL = 0.5 * (AD * CQ + BQ * BPE - A'T * A'B)},$$

in which

$$\mathbf{A'T = Sqrt(BQ * BQ - A'B * A'B)},$$

and **CQ** is as previously defined in figure 20.

When burning outer edge **A''D''** is situated so that **A''B < BV**, as in figure 21, then the sliver has burned out (burning edge lengths and end area are zero).

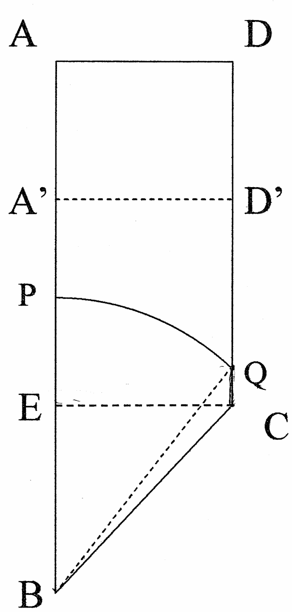


Figure 20. Type 1 LS SP – no burning surface inter-, section radius greater than diagonal.

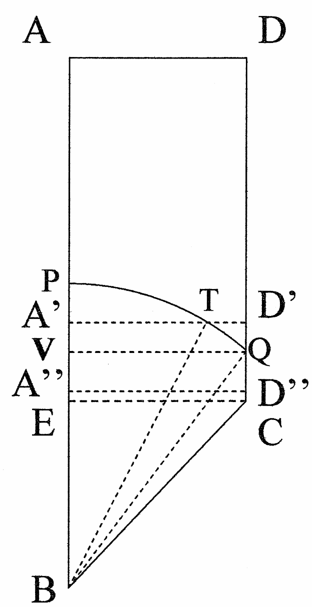


Figure 21. Type 1 LS SP – burning surface intersection, radius greater than diagonal.

4.1.3 Two Perforations

Figure 22 shows a trapezoidal type 1 propellant grain sliver with perforations centered at both inner corners. When the burning outer edge **A'D'** is positioned so that **CD' > CG** (radius of short side perforation), there is no intersection; burning outer edge length is **AD**, burning perforation edge length is the sum of arcs **GH** and **PQ** (defined in figures 6 and 18), and end area is reduced by

$$\mathbf{ENDS = 0.5 * CG * CG * (PI / 2 + Cos^{-1}(AD / BC)}$$

and

$$\mathbf{ENDL = 0.5 * BQ * BQ * Sin^{-1}(AD / BC)}.$$

When the burning outer edge has eclipsed the perforation on the short side (as in figure 9) and **A''B > BQ** (figure 22), then the calculations are as presented for figure 18.

In figure 23 when **A'D'** intersects the burning perforation edge on the short side (**CD' < CG** when **A'B > BE,** or when **A'B < BE** and **A'B > BE – BE * CG / BC**), then the calculations are as presented in figures 7 and 8 plus (a) the addition of the burning long-side perforation edge length and (b) the subtraction of the long-side perforation from the end-area computation.

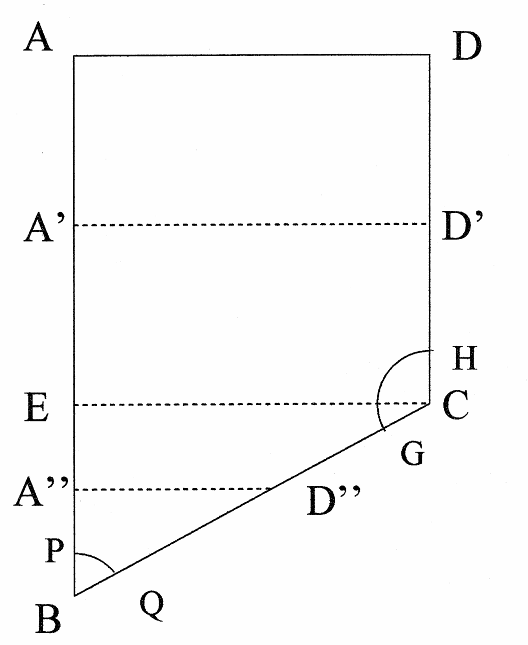


Figure 22. Type 1 two-perforation trapezoid – no burning arc intersection.

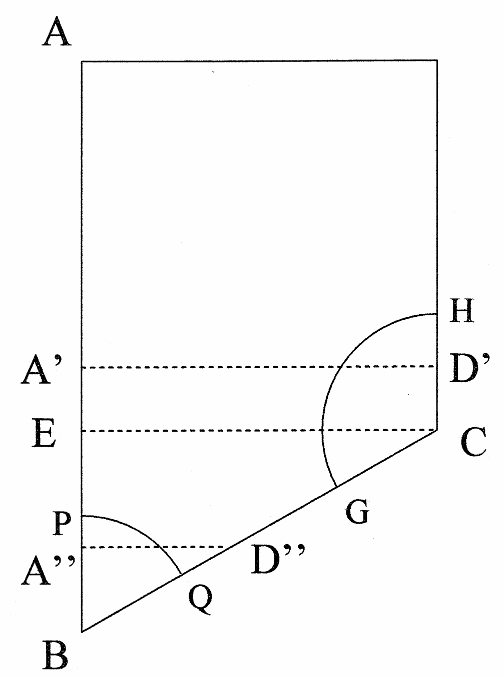


Figure 23. Type 1 TP – outer surface intersection with (one) burning arc, sum of radii less than diagonal.

If the burning outer edge eclipses the short-side perforation and intersects the long-side perforation edge (shown as **A''D''**), then the solutions for burning outer edge, burning perforation edge, and end area are as presented in figure 19.

Figure 24 shows the situation where the perforation radii are large enough that the burning outer edge can intersect both perforation edges at the same time, combining the two cases from figure 23.

When burning outer edge **A'D'** does not intersect the short-side perforation (**CD' > CG** and **A'B > BE**), but the sum of the radii exceeds the length of the line connecting the two centers (**BQ + CQ > BC** in figure 25), a triangle **BCQ** is formed and its area is calculated by the formula

$$\mathbf{AREA = Sqrt(S * (S - BC) * (S - BQ) * (S - CQ))}$$

in which

$$\mathbf{S = 0.5 * (BC + BQ + CQ)}.$$

Angles **BCQ** and **CBQ** can be found by

$$\mathbf{Angle\ BCQ = Sin^{-1}(2.0 * AREA / BC / CQ)}$$

and

$$\mathbf{Angle\ CBQ = Sin^{-1}(2.0 * AREA / BC / BQ)}.$$

Now the remaining perforation arc angles **EBQ** and **DCQ** can be found by

$$\mathbf{Angle\ EBQ = Sin^{-1}(AD / BC) - Angle\ CBQ}$$

and

$$\mathbf{Angle\ DCQ = PI / 2 + Cos^{-1}(AD / BC) - Angle\ BCQ},$$

leading to computations for burning perforation edge and end area reductions as

$$\mathbf{BPE = Angle\ EBQ * BQ + Angle\ DCQ * CG},$$

$$\mathbf{ENDS = 0.5 * Angle\ DCQ * CG * CG},$$

and

$$\mathbf{ENDL = 0.5 * Angle\ EBQ * BQ * BQ + AREA}.$$

Burning outer edge length in this case is **AD** since it does not intersect the perforations and **A'B > BE**.

When **BQ + CQ > BC**, **CD' < CG**, **A'B > BQ**, and **A'B > BE** as in figure 26, areas of triangle **BCQ** and angles **CBQ** and **BCQ** are all found as in the previous section. However, the burning perforation edge length of the short-side perforation, burning outer edge, and end area reduction calculations are as follow:

$$\mathbf{Angle\ FCQ = Angle\ DCQ - Cos^{-1}(CD' / CG)},$$

$$\mathbf{BPE = Angle\ EBQ * BQ + Angle\ FCQ * CG},$$

$$\mathbf{BOE = AD - Sqrt(CG * CG - CD' * CD')},$$

$$\mathbf{ENDS = 0.5 * (Angle\ FCQ * CG * CG + CD' * Sqrt(CG * CG - CD' * CD'))},$$

and

$$\mathbf{ENDL = 0.5 * Angle\ EBQ * BQ * BQ + AREA}.$$

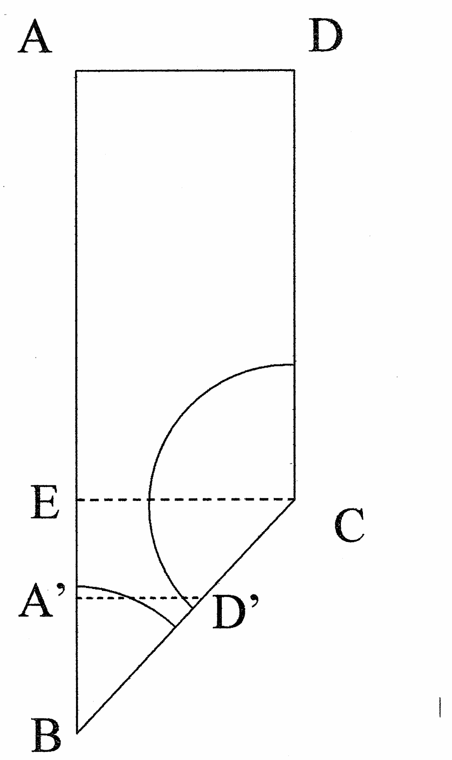


Figure 24. Type 1 TP – double intersection with outer surface, sum of radii less than diagonal.

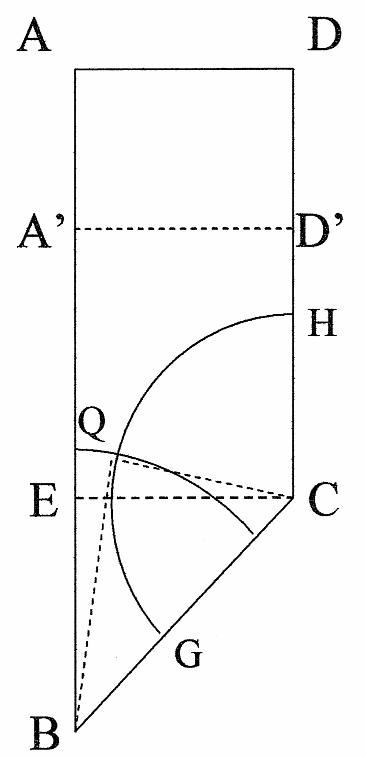


Figure 25. Type 1 TP – no outer surface intersection, sum of radii greater than diagonal.

If **BQ + CQ > BC**, **CD' < CG**, **BQ > A'B**, **A'B > BE**, and **A'B > BQ * Cos(EBQ)** as shown in figure 27, then the calculations are the same as for figure 26 except that burning perforation edge length is

BPE = Angle QBT * BQ + Angle FCQ * CG,

in which

Angle QBT = Angle EBQ - $\mathbf{Cos^{-1}}$(A'B / BQ).

Also, the burning outer edge and long-side end area subtractions are computed as

BOE = AD – Sqrt(CG * CG – CD' * CD') – Sqrt(BQ * BQ – A'B * A'B),

and

ENDL = 0.5 * (Angle QBT * BQ * BQ + A'B * Sqrt(BQ * BQ – A'B * A'B)) + AREA.

When **A'B < BQ * Cos(EBQ)**, then the trapezoidal sliver has burned out.

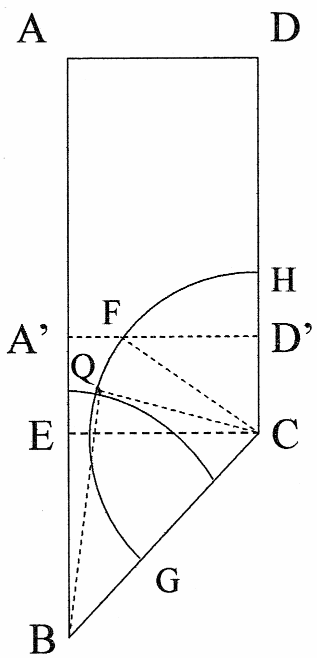


Figure 26. Type 1 TP – outer surface intersects with short-side perforation arc, sum of radii greater than diagonal.

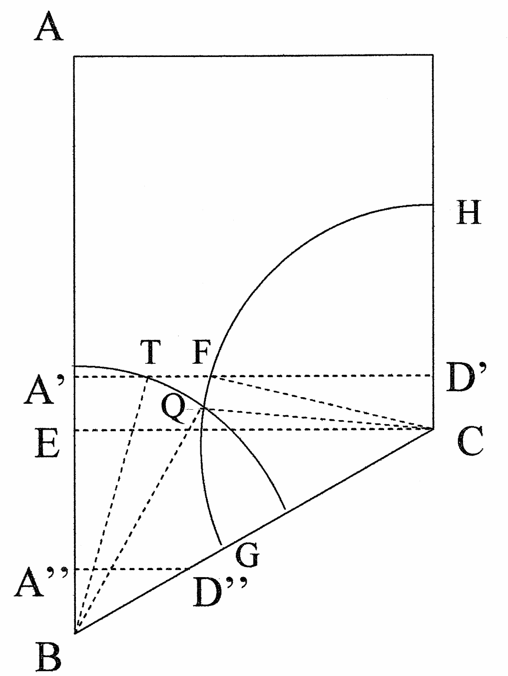


Figure 27. Type 1 TP – outer surface intersects both arcs, sum of radii greater than diagonal.

In figure 28 where **BQ + CQ > BC**, **CD’ < CG**, **BQ < A’B**, **A’B < BE**, and **A’B > BQ * Cos(EBQ)**, the burning perforation edge is now

$$\textbf{BPE = Angle EBQ * BQ + Angle FCQ * CG}$$

in which

$$\textbf{Angle FCQ} = \textbf{Cos}^{-1}\textbf{(AD / BC) – Angle BCQ –} \textbf{Sin}^{-1}\textbf{(A'E / CG)}.$$

Burning outer edge **A’F** is calculated as

$$\textbf{BOE = AD – Sqrt(CG * CG – A'E * A'E)}.$$

Trapezoidal end area reductions are

$$\textbf{ENDS = 0.5 * Angle FCQ * CG * CG},$$

and

$$\textbf{ENDL = 0.5 * Angle EBQ * BQ * BQ + AREA}.$$

When **BQ + CQ > BC**, **CD’ < CG**, **BQ > A’B**, **A’B < BE**, and **A’B > BQ * Cos(EBQ)** (figure 29), angle **QBT** is as calculated from figure 27 while angle **FCQ** is from figure 28. Burning perforation edge is

$$\textbf{BPE = Angle QBT * BQ + Angle FCQ * CG},$$

while burning outer edge and short-side end area reduction are as calculated in figure 27. Long-side end area reduction is

ENDL = 0.5 * (Angle EBQ * BQ * BQ + A’B * A’T) + AREA

in which

A’T = Sqrt(BQ * BQ – A’B * A’B).

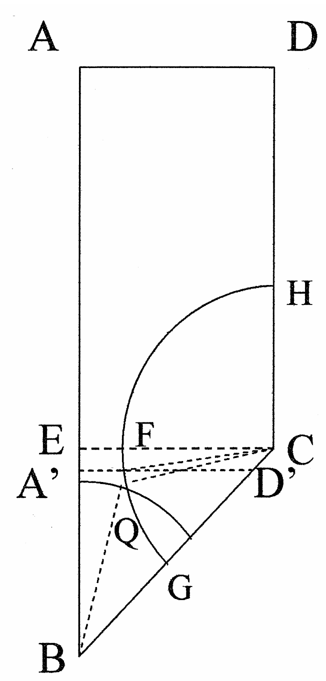


Figure 28. Type 1 TP – sum of radii greater than diagonal, outer surface intersects SS arc beyond perforation center arcs.

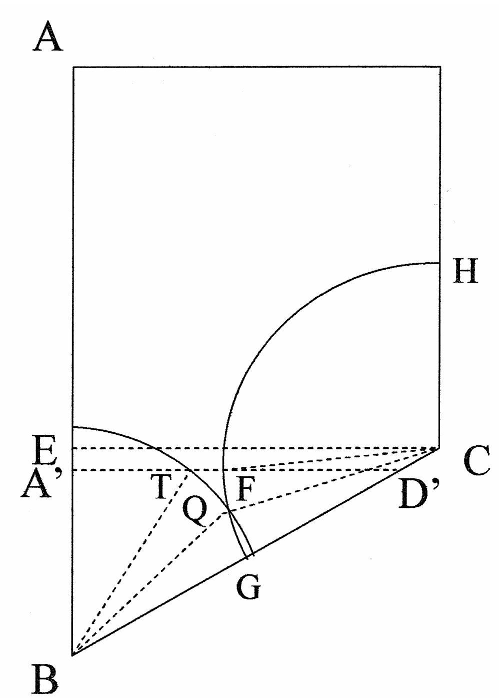


Figure 29. Type 1 TP – sum of radii greater than diagonal, outer surface intersects both beyond SS perforation center.

The calculation for angle **BCQ** (from figure 25) uses the inverse sine function, which always gives its result in the range from **0.0** to **PI / 2**. If **BCQ** is greater than **PI / 2**, as shown in figure 30, a check for the angle is given by a comparison of the square of length **BQ** against the sum of squares of lengths **BC** and **CQ**. By the Pythagorean theorem, if angle **BCQ** is a right angle, then

BQ = Sqrt(BC * BC + CQ * CQ).

When **BQ** is greater than root of the sum of squares, then angle **BCQ** is reset as

Angle BCQ = PI – Sin^{-1}**(2.0 * AREA / BC / BQ)**.

If **BQ > BC** and **EV > CG** (where **EV = Sqrt(BQ * BQ – AD * AD) – BE**), then the long-side perforation has eclipsed the short-side perforation as in figure 31. Calculations for end area and burning edge lengths revert to those for figures 20 and 21.

If **CG > CE** and **BQ > BK** as in figure 32 where

BK = BE – Sqrt(CG * CG – AD * AD),

then the short-side perforation has overtaken the long-side burning arc and the solutions for end area and burning edge lengths are as found for figures 15, 16, and 17.

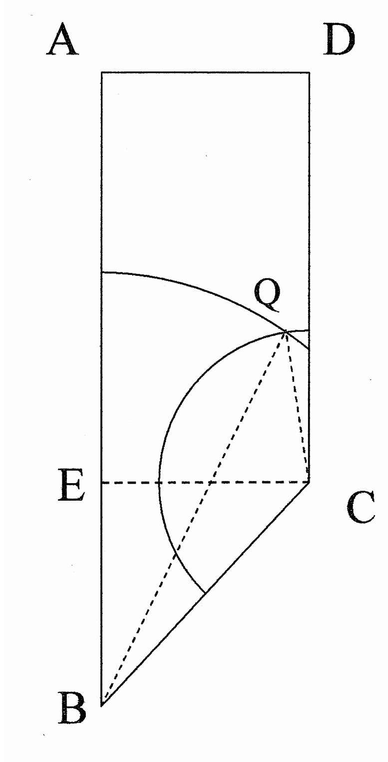


Figure 30. Type 1 TP – LS arc radius greater than diagonal, perforation arcs intersect.

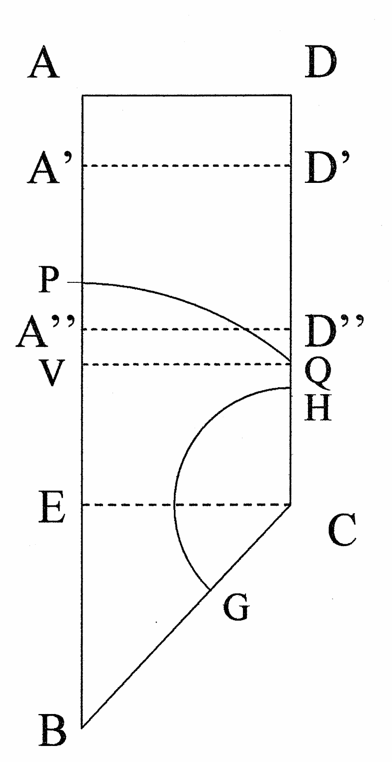


Figure 31. Type 1 TP – LS arc eclipses SS perforation.

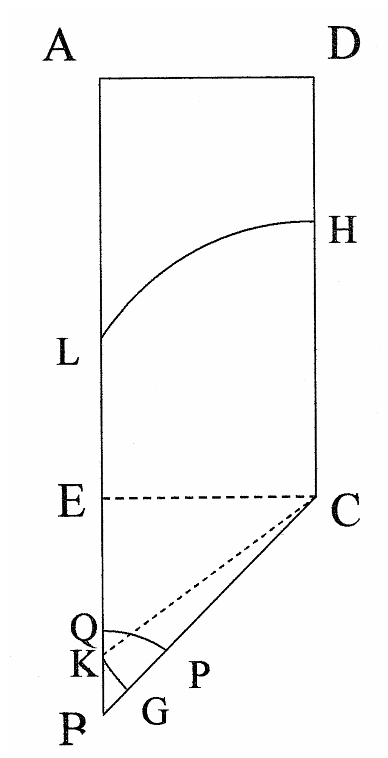


Figure 32. Type 1 TP – SS arc eclipses LS perforation.

4.2 Type 2 Trapezoid

The type 2 trapezoid will be defined as having the line connecting centers of the inner corner perforations lying perpendicular to the sides (figure 33). Burning outer surface is line **AD**. In figure 34, line **A'D'** is the burning outer surface position corresponding to a burned depth of **A'E**.

Because the measurement of burned depth is perpendicular to the burning surface, the equation for reduction in side length because of a burning depth of **A'E** is

AA' = DD' = A'E * AD / BC,

and the following analysis will refer to a "modified burned depth" as **AA'** when the actual burned depth is **A'E**.

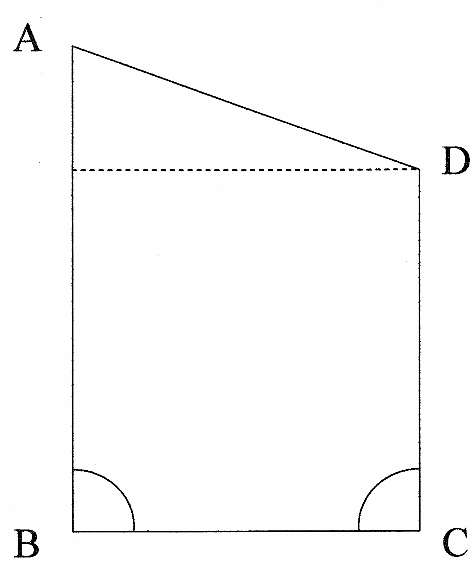


Figure 33. Type 2 trapezoid – perforations at inner corners.

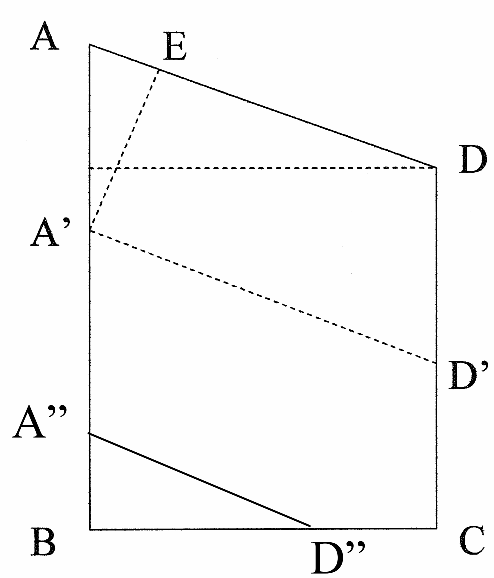


Figure 34. Type 2 trapezoid – measurement of outer surface burn depth.

Two equations will describe nominal end area for all the following type 2 sliver analysis. Sliver end area when modified burned depth is **AA'** is

END = 0.5 * BC * (A'B + CD')

until modified burn depth is greater than **CD** (as shown with line **A''D''** in figure 34), then end area is simply

END = 0.5 * A''B * BD''

in which

BD'' = A''B * BC / (AB - CD).

At this time, burning outer edge is reduced from length **AD** to **A''D''** where

BOE = A''D'' = AD * BD'' / BC.

4.2.1 Single Perforation on Long Side

If a perforation is centered at the inner end of the long side, as in figure 35 where the perforation radius is **BQ**, then when **BQ < BC**, the end area is reduced by

ENDL = 0.5 * PI / 2 * BQ * BQ = PI * BQ * BQ / 4.

Burning outer edge length is **AD** and burning perforation arc length is

BPE = 0.5 * PI * BQ.

To check whether the burning outer edge intersects the perforation arc, a comparison should be made between perforation radius and the length of a line drawn from corner **B** to a point **F** on the outer edge such that **BF** is perpendicular to **A'D'** (figure 35). The length of **BF** is calculated by

BF = BC * A'B / AD.

When **BF < BQ**, **BQ < BC**, and modified burn depth is less than **CD**, as in figure 36, and the remaining long side length is greater than the perforation radius as shown with line **A'D'** (where **A'B > BQ**), then the burning outer edge intersects the perforation at two points labeled **W** and **Z** where

FW = FZ = Sqrt(BQ * BQ – BF * BF).

Burning outer edge length is **AD – FW – FZ**, and burning arc length is

BPE = (PI / 2 – 2 * Cos^{-1}(BF / BQ)) * BQ.

End area reduction is now

ENDL = 0.5 * BQ * BPE + BF * FW.

If **BF < BQ**, **A'B < BQ**, **BQ < BC**, and modified burn depth is less than **CD** as in figure 37, then burning outer edge is

BOE = AD – A'Z

in which

A'Z = (AB – CD) * BF / BC + Sqrt(BQ * BQ – BF * BF).

Burning perforation edge is calculated as

BPE = (PI / 2 – Cos^{-1}(BF / A'B) – Cos^{-1}(BF / BQ)) * BQ,

and end area reduction is

ENDL = 0.5 * (BF * A'Z + BPE * BQ).

Figure 38 shows the situation where **BF < BQ**, **A'B > BQ**, **BQ < BD' < BC**, and modified burn depth is greater than **CD**. **BD'** is defined as

BD' = BC * A'B / (AB – CD).

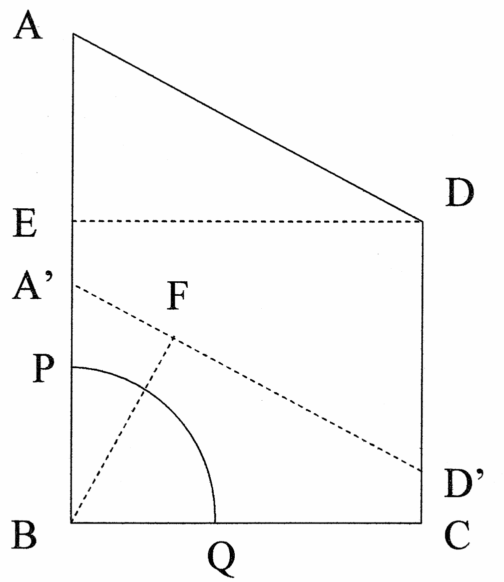


Figure 35. Type 2 long-side single-perforation trapezoid – no intersection with outer burning surface.

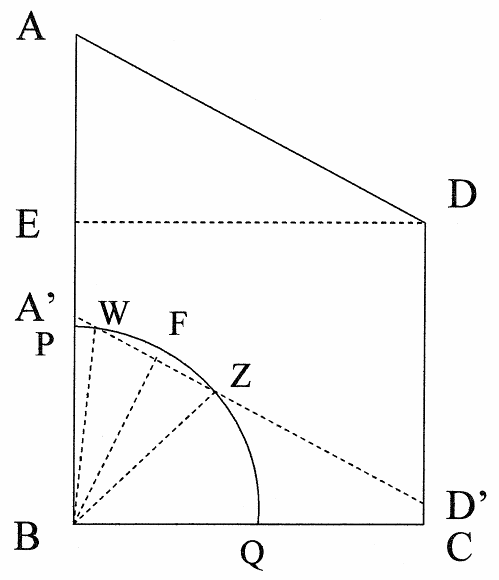


Figure 36. Type 2 LS SP – double arc intersection with burning surface, burned depth less than short-side length.

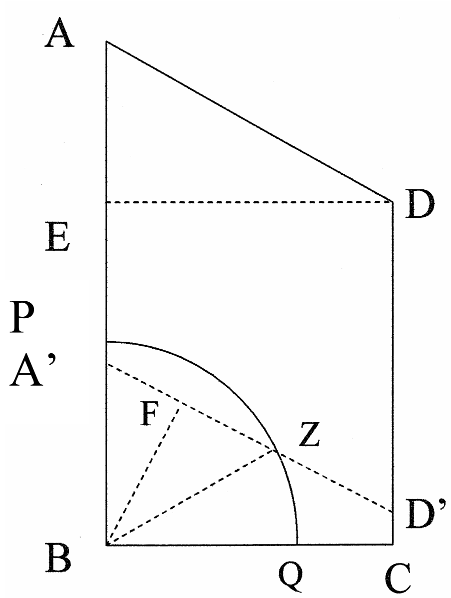


Figure 37. Type 2 LS SP – single arc intersection, burned depth less than SS length.

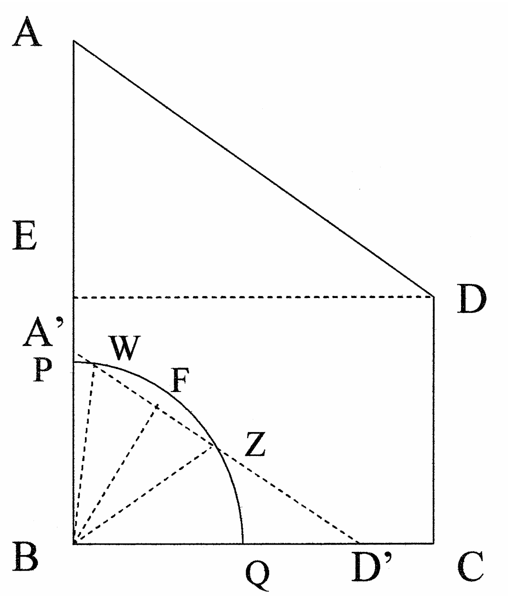


Figure 38. Type 2 LS SP – double arc intersection, burned depth greater than SS length.

Here the burning outer edge length is

BOE = A’D’ – 2 * FZ = AD * A’B / (AB – CD) – 2 * Sqrt(BQ * BQ – BF * BF),

and the equations for burning perforation arc length and end area reduction are the same as for figure 36.

When **BF < BQ**, **A'B > BQ**, **BD' < BQ < BC**, and modified burn depth is greater than **CD** as in figure 39, then

$$\mathbf{BOE = A'D' - D'W},$$

in which

$$\mathbf{D'W = AD * A'B / (AB - CD) - Sqrt\,(BQ * BQ - BF * BF) - BD' * (AB - CD) / AD}.$$

The remaining burning perforation edge length is computed as

$$\mathbf{BPE = (PI / 2 - Cos^{-1}[BF / BQ] - Cos^{-1}[BF / BD']) * BQ},$$

and end area is reduced by

$$\mathbf{ENDL = 0.5 * (BPE * BQ + BF * [Sqrt\,\{BQ * BQ - BF * BF\} + BD' * \{AB - CD\} / AD])}.$$

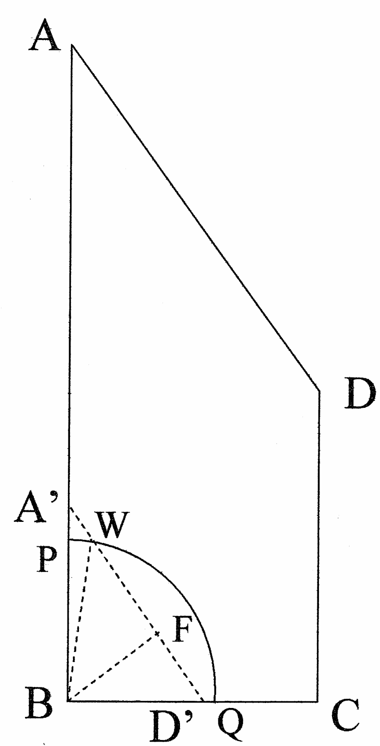


Figure 39. Type 2 LS SP – single arc intersection (long side), burned depth greater than SS length.

In figure 40, **BF < BQ**, **A'B < BQ**, **BD' > BQ**, **BQ < BC**, and modified burn depth is greater than **CD**. Burning outer edge length is calculated as

$$\mathbf{BOE = AD * A'B / (AB - CD) - (AB - CD) * BF / BC - Sqrt(BQ * BQ - BF * BF)}$$

and the equations for burning arc length and end area reduction are the same as in figure 37.

When **A'B < BQ** and **BD' < BQ** as in figure 41, the propellant sliver has burned out. (Length **BD'** is as defined in figure 33.)

When **BF > BQ** and **BQ > BC**, shown in figure 42, burning outer edge length is **AD**, burning perforation arc length is

$$\mathbf{BPE = (PI / 2 - Cos^{-1}(BC / BQ)) * BQ},$$

and end area reduction is

$$\mathbf{ENDL = 0.5 * (BPE * BQ + BC * Sqrt(BQ * BQ - BC * BC)}.$$

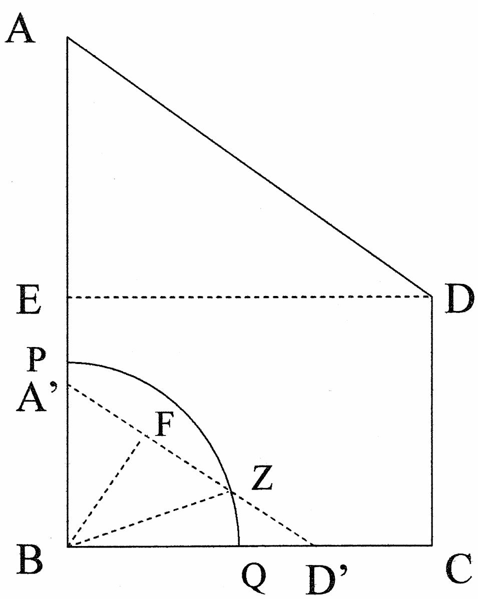


Figure 40. Type 2 LS SP – single arc intersection (short side), burned depth greater than SS length.

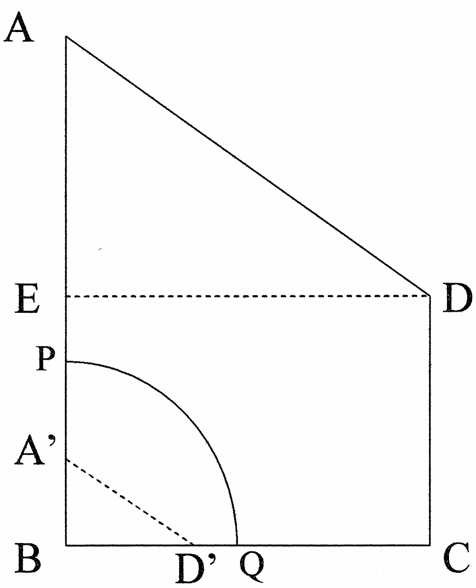


Figure 41. Type 2 LS SP – burnout.

For figure 43 where **BF < BQ**, **A'B > BQ**, **BQ > BC**, and **CD' > Sqrt(BQ * BQ – BC * BC)**, then burning outer edge length is as computed for figure 36, and burning perforation edge length is

$$\mathbf{BPE = (PI / 2 - 2 * Cos^{-1}(BF / BQ) - Cos^{-1}(BC / BQ)) * BQ}.$$

End area reduction for figure 43 is

$$\mathbf{ENDL = 0.5 * (BPE * BQ + 2 * BF * FZ + BC * Sqrt(BQ * BQ - BC * BC)}.$$

When **BF < BQ**, **A'B < BQ**, **BQ > BC**, and **CD' > Sqrt(BQ * BQ – BC * BC)** as shown in figure 44, burning outer edge length is as found for figure 37. Burning perforation edge length is

$$\mathbf{BPE = (PI / 2 - Cos^{-1}(BF / A'B) - Cos^{-1}(BF / BQ) - Cos^{-1}(BC / BQ)) * BQ}.$$

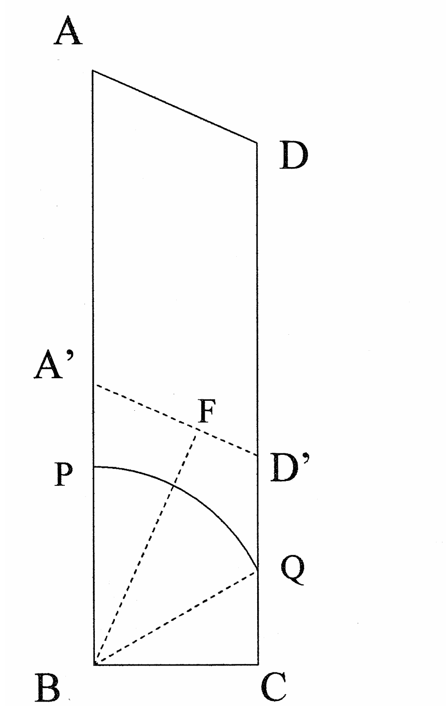


Figure 42. Type 2 LS SP – arc radius greater than width, no burning surface intersection.

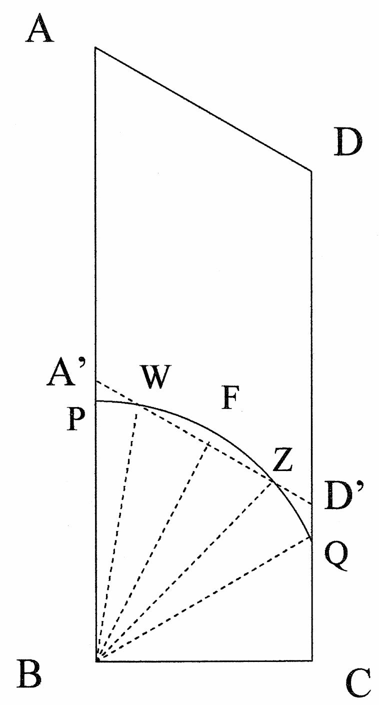


Figure 43. Type 2 LS SP – arc radius greater than width, double arc intersection.

For figure 44, the end area reduction is found by

ENDL = 0.5 * (BPE * BQ + BF * A'Z + BC * Sqrt(BQ * BQ – BC * BC)

in which **A'Z** is as calculated in figure 37.

If the situation arises when **BF < BQ**, **A'B > BQ**, **BQ > BC**, and **CD' < Sqrt(BQ * BQ – BC * BC)**, as depicted in figure 45, then **A'W** is burning outer edge length and is calculated as

BOE = AD – Sqrt(BQ * BQ – BF * BF) – Sqrt(BD' * BD' – BF * BF)

in which

BD' = Sqrt(BC * BC + CD' * CD').

Burning perforation edge length is

BPE = (PI / 2 – $\mathbf{Cos^{-1}}$(BF / BQ) – $\mathbf{Cos^{-1}}$(BF / BD') – $\mathbf{Cos^{-1}}$(BC / BD')) * BQ

and end area is reduced by

ENDL = 0.5 * (BPE * BQ + BF * (AD – BOE) + BC * CD').

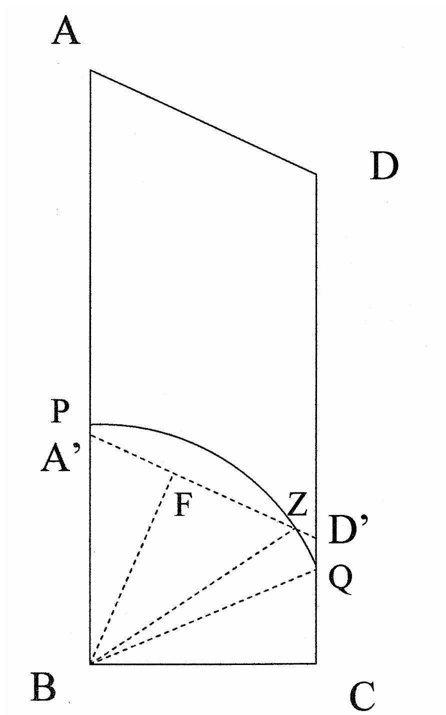


Figure 44. Type 2 LS SP – arc radius greater than width, short-side burning surface intersection.

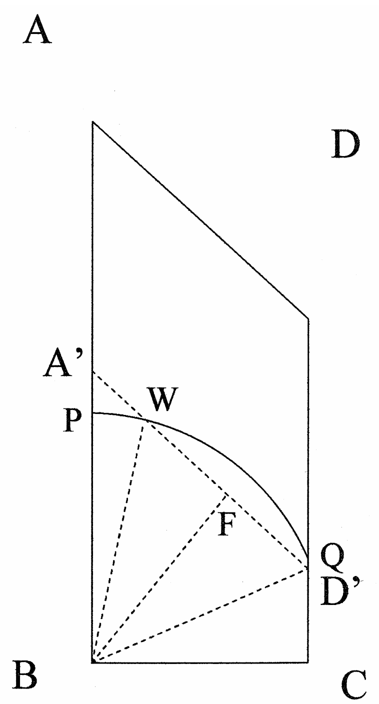


Figure 45. Type 2 LS SP – arc radius greater than width, long-side burning surface intersection.

4.2.2 Single Perforation on Short Side

In figure 46, a perforation is centered on inner corner **C** of a type 2 trapezoid. When the current length of the short side (**CD’**) is greater than or equal to the length of the perforation radius (**CG**),

BOE = AD

and the end area reduction attributable to the short-side perforation is

ENDS = PI * CG * CG / 4.

The length of the burning perforation edge is

BPE = PI * CG / 2.

When **CD’** is greater than zero but less than the perforation radius (figure 47), the intersection (point **J**) of the burning outer edge and the perforation arc can be found through geometric formulae for a line and circle and from the quadratic formula. The line **A’D’** is represented by

Y = Mx + B,

in which **M** is the slope of **A’D’**, and **B** is the intercept (**CD’**). Let point **C** be the origin for the drawing, and allow directions to **X** and **Y** be positive. Then **M** is found as

M = (AB – CD) / BC.

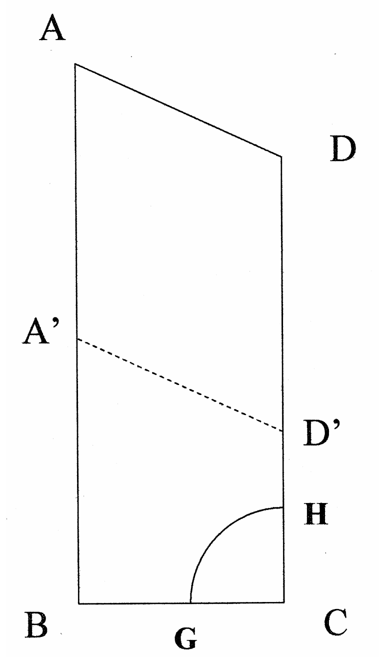


Figure 46. Type 2 short-side single-perforation trapezoid – no intersection of burning surfaces.

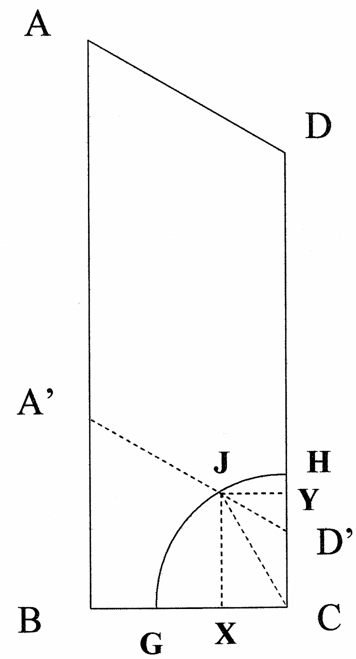


Figure 47. Type 2 SS SP – outer burning surface intersects perforation arc (radius less than width, burned depth less than short-side length).

The circle centered at point **C** is defined as

$$Y = Sqrt(CG * CG – x * x).$$

Equating the square of the **Y** value at point **J** for both line and circle gives

$$M * M * x * x – 2 * M * CD' * x + CD' * CD' = CG * CG – x * x.$$

Collecting terms and putting into a quadratic equation leaves

$$(M * M + 1) * x * x – (2 * M * CD') * x + CD' * CD' – CG * CG = 0,$$

which can be solved for **x**. Then substituting **x** back into one of the equations for **Y** gives both values for **JX** and **JY** in figure 47. Angle **JCG** is found as $Sin^{-1}(JX / CG)$ and angle **JCY** is $Sin^{-1}(JY / CG)$, giving the end area lost because of the perforation as

$$ENDS = 0.5 * CG * CG * Sin^{-1}(JX / CG) + 0.5 * CD' * CG * Sin^{-1}(JY / CG).$$

The length of the burning perforation edge is

$$BPE = CG * Sin^{-1}(JX / CG),$$

and length of burning outer edge

$$BOE = A'D' – A'D' * JY / BC.$$

In figure 48, the trapezoid short side has been overrun by the burning outer edge. Point **J** and lengths **JX** and **JY** can be found in a similar manner to figure 47, but the equation for end area subtraction is

$$\mathbf{ENDS = 0.5 * CG * CG * Sin^{-1}(JX / CG) - 0.5 * CD' * CG * Sin^{-1}(JY / CG),}$$

in which **CD' = BC – A'D' * BC / AD and A'D' = AD * A'B / (AB – CD).**

The calculations for burning edges are the same as for figure 47.

Figure 49 shows eclipse of the perforation whenever **CD'** is greater than **CG**. In this case, **BPE** and **ENDS** are zero, and

$$\mathbf{BOE = AD * A'B / (AB - CD).}$$

When the perforation radius is greater than trapezoid width, as in figure 50 where there is no intersection of perforation arc with outer burning edge,

$$\mathbf{BOE = AD,}$$

$$\mathbf{BPE = CG * Sin^{-1}(BG / BC),}$$

and

$$\mathbf{ENDS = 0.5 * BG * BC + 0.5 * CG * CG * Sin^{-1}(BG / BC)}$$

in which

$$\mathbf{BG = Sqrt(CG * CG - BC * BC).}$$

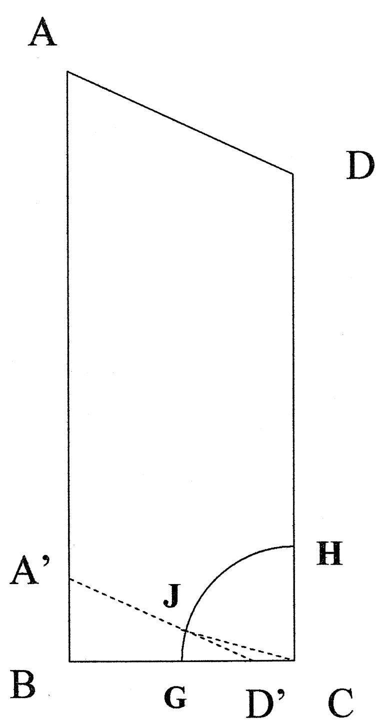


Figure 48. Type 2 SS SP – outer burning surface intersects perforation arc (radius less than width, burned depth greater than short side).

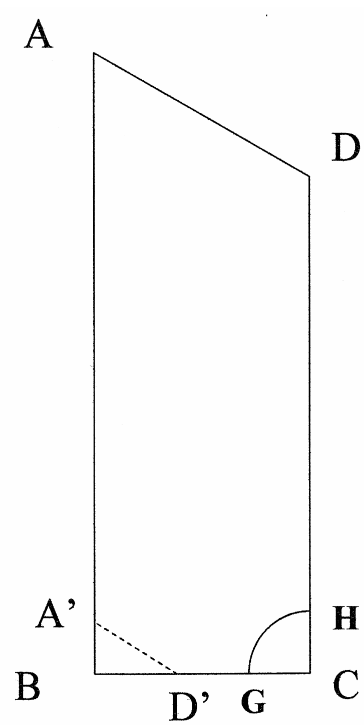


Figure 49. Type 2 SS SP – no intersection of burning surfaces, burned depth greater than short-side length.

The intersection of outer edge and perforation arc, when perforation radius is greater than trapezoid width, is shown in figure 51. Again, point **J** and lengths **JX** and **JY** can be found as for figure 47. Length **BG** is found as in the previous figure.

$$\mathbf{BOE = AD - AD * CX / BC}.$$

$$\mathbf{BPE = CG * (Sin^{-1}(JY / CG) - Sin^{-1}(BG / BC))}.$$

Area reduction attributable to the perforation is

$$\mathbf{ENDS = 0.5 * BG * BC + 0.5 * CG * CG * (Sin^{-1}(JY / CG) - Sin^{-1}(BG / BC))}.$$

When current long-side length is less than **BG**, the trapezoid has burned out, as shown by line **A''D''** in figure 51.

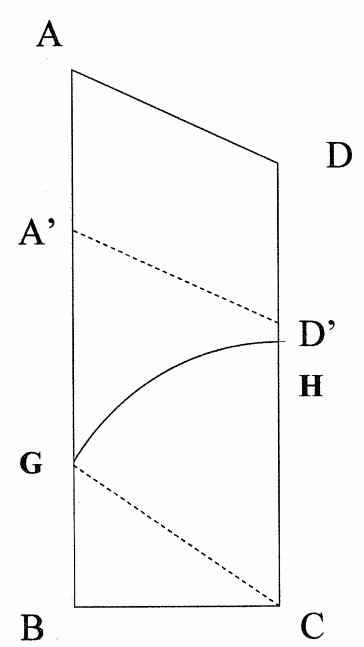


Figure 50. Type 2 SS SP – no intersection of burning surfaces, arc radius greater than width.

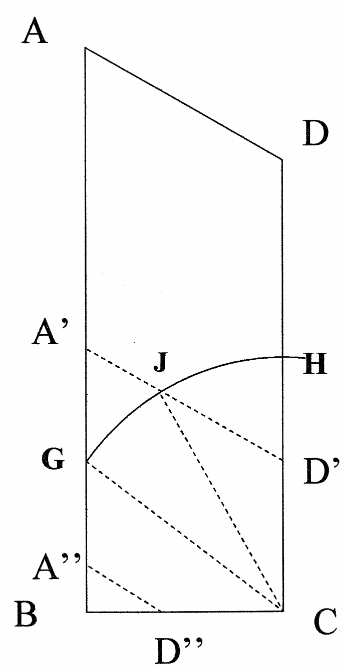


Figure 51. Type 2 SS SP – outer burning surface intersects perforation arc, arc radius greater than width

4.2.3 Two Perforations

When perforations are present at each of the inner trapezoid corners, the sum of the two single-perforation methods may be used until the perforations intersect each other. At that time, a computation may be made for the point of intersection relative to the long-side inner corner. The distance can then be used for a reduced base trapezoid solution for the long side only where the current long-side length and a modified short-side length (depending on the ratio of the computed intersection base distance versus the original base width) are used with only the long-side perforation extant. When this is finished, a second computation is made with the modified

side length, the current short-side length, and the remaining base width with only the short-side perforation present. In figure 52, the procedure is defined by trapezoid **ABFE** with the long-side procedures, then by trapezoid **EFCD** with the short-side computations. The sum of the areas, arcs, and burning edges is calculated for a final solution.

We calculate distance **BF** by solving two equations for perforation circles. The equation for the long-side circle is

FY = Sqrt(BQ * BQ – BF * BF),

while the equation for the short-side circle (with corner **B** as the common origin) is represented by

FY = Sqrt(CG * CG – (BC – BF) * (BC – BF)).

The common solution is

BF = (BQ * BQ – CG * CG + BC * BC) / (2 * BC)

in which **BF** is the 'x'-distance from the origin to where the circles intersect. Figure 53 shows that if the circles are of unequal radii, the intersection is not at the mid-point of the original trapezoid base.

When base **BF** is known, the side **EF** length can be computed as

EF = AB * (BC – BF) / BC.

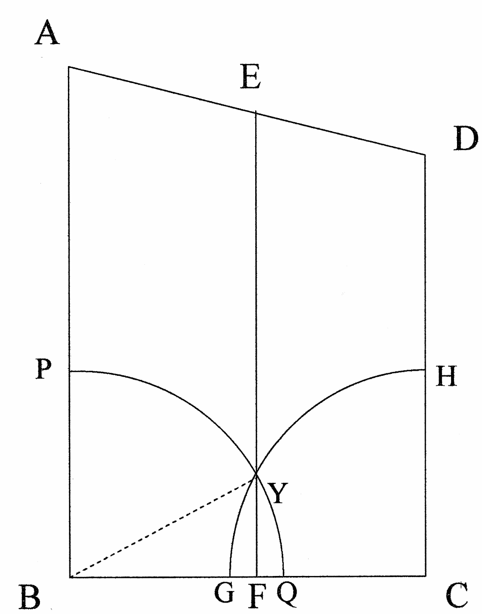


Figure 52. Type 2 double-perforation trapezoid – sum of equal radii greater than width.

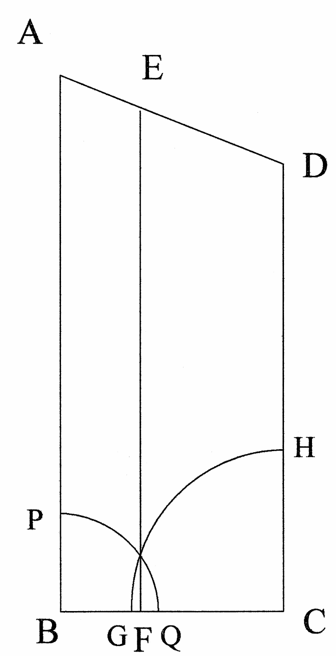


Figure 53. Type 2 DP – sum of unequal radii greater than width.

4.3 Circular or Single-Perforation Slivers

A circular section grain sliver is defined by four parameters: inner diameter (if perforated), outer diameter, arc size, and sliver length. Figure 54 shows the end of a single-perforation grain sliver of outer radius **OA**, inner radius **OB**, and an arc of **BOC** radians (sliver length is not shown here). Outer surface burning edge length is

$$\mathbf{BOE = (Angle\ BOC) * OA},$$

burning perforation edge length is calculated as

$$\mathbf{BPE = (Angle\ BOC) * OB},$$

and end area as

$$\mathbf{END = 0.5 * (OA * BOE - OB * BPE)}.$$

As the grain sliver burns, **OA** is reduced and **OB** increases. When **OB** is equal to or greater than **OA**, the sliver has burned out. Then the burning edges and end area are set to zero.

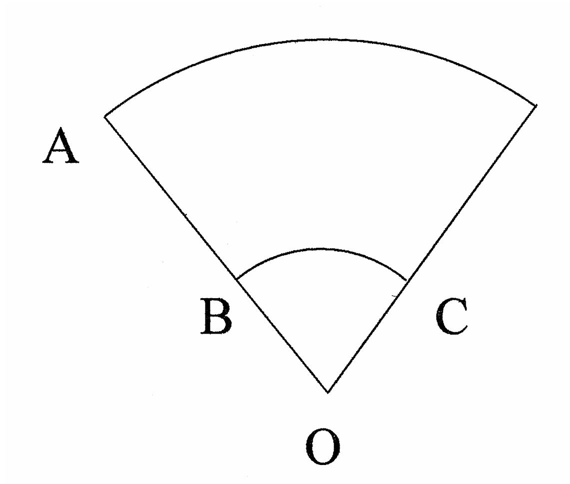


Figure 54. End view of segment from single-perforation cylindrical grain.

4.4 Triangular Slivers

The equations for calculating end area and burning perforation arc length for an equilateral triangular sliver are taken from the 1982 report by Franz Lynn (*3*) and used in the IBHVG2 computer code for interior ballistic simulations. The method keeps track of the initial triangular area and accounts for the burned end area portion at each burned depth. Figures 55 and 56 show initial geometry and a partially burned drawing of the end area.

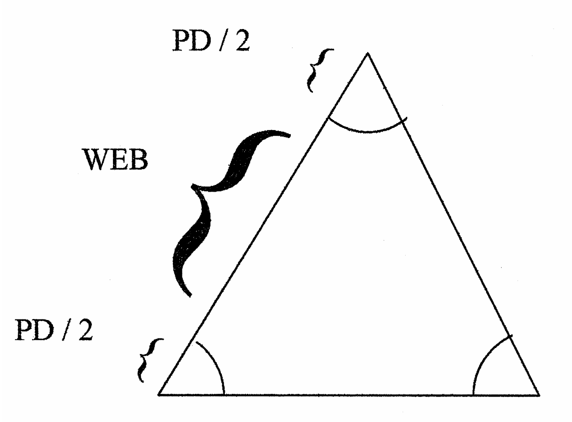


Figure 55. Triangular inner sliver, end view.

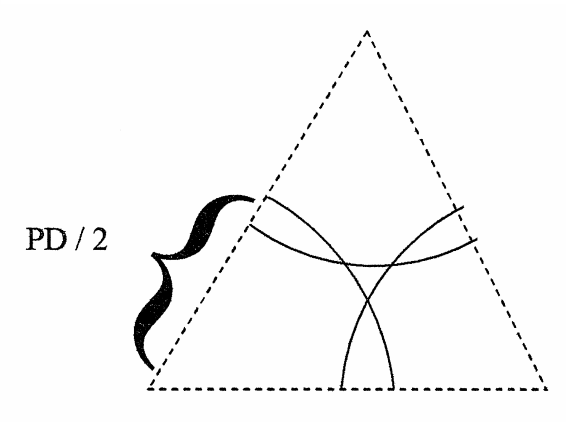


Figure 56. Triangular inner sliver, end view, perforations intersecting.

5. Program for Adding Slivers

A control program has been developed for the geometric analysis. Each type of grain sliver has a routine included to compute end area, burning outer edge length, and burning perforation arc length. Variables are entered in the controller to keep track of sliver definitions, geometry, lengths, and number of instances.

As the program does its calculations, the burned depth is increased at each iteration and each type of sliver is calculated. End areas and burning edge lengths are summed and multiplied by current sliver length in order to find total grain volume and burning surface area. An iteration data card is used to enter the step size to use for burning depth increment and a multiplier for output values to simulate a number of grains as in a full propelling charge.

5.1 Input File

A sample input file is printed as appendix A where a propelling charge of 11,360 19-perforated hexagonal grains (as in figure 1) is described. All input lines with a "c" in the first column are treated as comments; the file contains several lines describing input variables for each type of sliver and a set of control parameters. In general, columns 1 through 3 contain a right-adjusted integer describing the type of input on the rest of the line; all other values are floating point numbers. Input types 1 through 4 are grain slivers; columns 4 through 10 on these lines contain the number of like slivers included to compose the total grain. The first non-comment card in the file specifies sliver type 1, with 12 instances of the trapezoidal geometry followed by the defining lengths in columns 11 through 70. In order to fully describe the trapezoid, values are needed for trapezoid width, side lengths, perforation diameters, and grain length in order to compute the final volume. Similar variables are needed for a trapezoidal type 2 sliver.

The next non-comment line contains values describing a circular single-perforated sliver (type 3). First parameter input is the number of slivers to be considered (six). The geometric values needed are the diameter of the inner perforation if the sliver has one; if not, a value of 0.0 is used to specify that the described sliver is a portion of a solid stick. The next necessary length is the diameter of the arc forming the outer surface, followed by the circle segment radius to be calculated (in radian measure). The last value is the length of the sliver.

Next input card is a description of an inner triangular grain sliver (type 4). There are 24 of these slivers in the grain being simulated. The necessary geometric values include a measure of the perforation diameter, the web length (initial distance between perforation arcs), and grain sliver length. For this test case, perforation diameter is 0.06604 cm, web distance is 0.116078 cm, and grain length is 1.70688 cm.

The final input card is a control parameter line (type 5). Parameter values include a burning depth increment and a number of grains to be simulated. The latter value is a multiplier for output values of volume and surface area; it defaults to 1 if the input value is zero or negative. For this application, the multiplier is 11360.0, as the output will be compared to an IBHVG2 calculation with 11,360 similar geometry grains in a charge simulation.

5.2 Output File

The output file (saved in FORTRAN [Formula Translator] file 7 during the calculation) from the previous input deck is shown in appendix B. The first four lines are a copy of the input parameters. Columns of calculated values follow: the left-hand column is a percentage of burned charge (or grain) at the present depth-burned value, as given in column 2. The third column is current volume of the unburned propellant; the fourth column contains total current surface area. The fifth, sixth, and seventh columns are calculated end area, perforation surface area, and lateral grain surface area, respectively. Each of the values in the last five columns has been multiplied by the control card value for number of grains in the charge, which in this case is 11360.

An inspection of the perforation surface area values shows increases until the depth-burned value reaches 0.059, at which time, the inner triangular sliver perforations have burned through to each other. At the same time, the outer surfaces of the trapezoidal grains have burned through to the inner perforation edges, and the circular single-perforation sliver outer and inner arcs have burned away the intervening propellant. Perforation and lateral surface areas rapidly fall until reaching a value of 0.0 at a burned depth of 0.081 (units here are centimeters, although never explicitly specified in the input or output prints). End area declines through the entire calculation.

6. Test Versus IBHVG2 19H Grain

The IBHVG2 interior ballistic simulation program has the capability to print current depth burned and charge granular surface area during a simulation. A charge of 11,360 19-perforation grains with the same geometry as the previous example calculates granular depth-burned and charge surface area printed in appendix C. A graphical comparison of the IBHVG2 results from appendix C plotted with the generic grain values from appendix B is shown in figure 57, where depth burned is the horizontal axis and total surface area is graphed to the vertical axis.

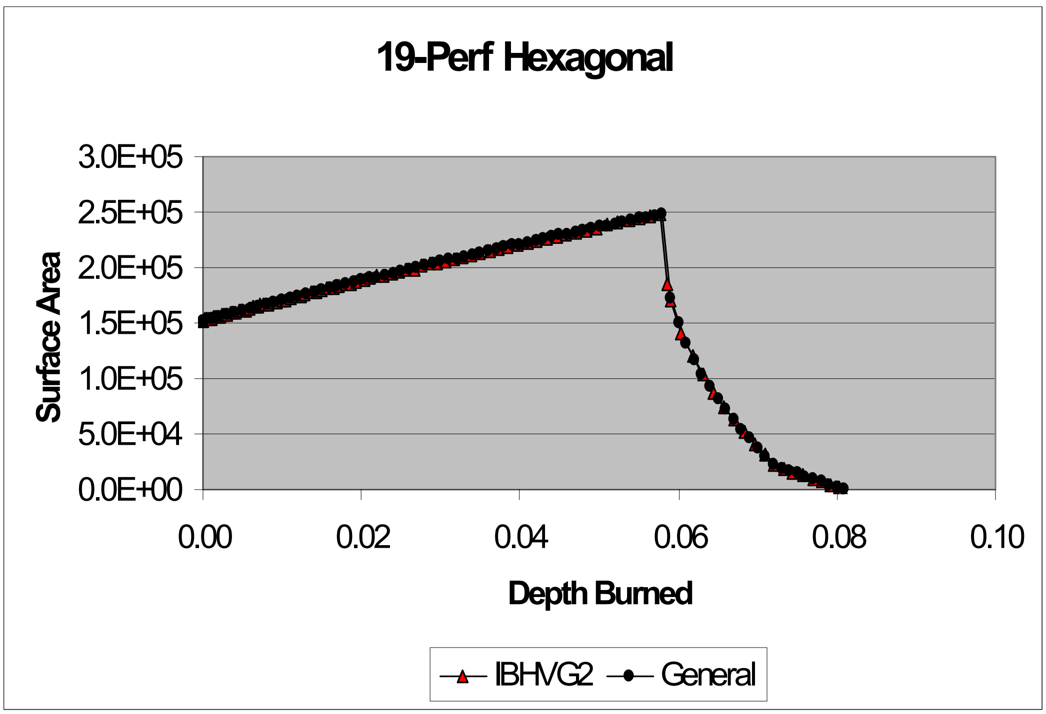


Figure 57. Comparison of IBHVG2 computed values with generic grain results.

7. Test Versus IBHVG2 19-Perforation Circular Grain

The 19-perforation hexagonal grain slivers are completely compatible with the types of slivers modeled with the generic grain program. If parts of a grain end area cannot be directly modeled by the four types of grain slivers, then an adaptation needs to be made in order to produce a usable simulation. A 19-perforated circular grain end is portrayed in figure 58, and an IBHVG2 simulation output with this grain geometry is printed as appendix D. The propellant deck in this calculation uses 10,057 grains in order to reach its designated charge weight.

The outer slivers of the 19-perforation cylindrical grain are now bound by a circle whose radius is one-half the major diameter of the grain. With one-sixth of the grain end as outlined in figure 58, the slivers can be mapped for simulation in a generic grain input deck. The inner slivers numbered 1 through 4 are simply standard inner triangular slivers and can be modeled directly (24 in the entire grain end). Outer slivers 5 and 10 are mirror image copies of each other; if **PD** is the perforation diameter and **WEB** is the measure of web distance (length **BD** minus one-half the perforation diameter in figure 59), then the distance from perforation center at **D** to the outside surface is **WEB + PD / 2**. The angle **BDF** is **PI / 6**, so slivers 5 and 10 can be estimated by single-perforation slivers of outer diameter **2 * WEB + PD**, inner diameter **PD**, and arc size **PI / 6**. Twelve of these slivers exist in the grain end.

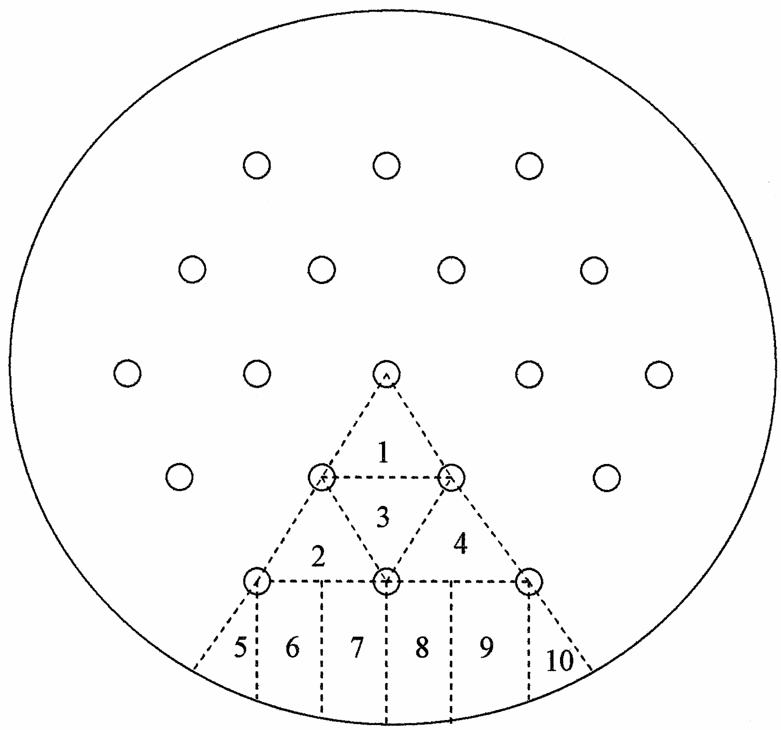


Figure 58. Circular 19-perforation grain end.

Slivers 6 through 9 will be modeled as type 2 trapezoidal slivers, since the line connecting inner corners is perpendicular to the sides. Although sliver **DFKN** (figure 59) could be simulated as a single sliver, the separation into two parts (**DFGM** as sliver 6 and **GHNM** as sliver 7) should result in less error because of the closer approximation of the outer sliver burning edge (arc **FGH**). Calculation of the side lengths is accomplished as follows:

DF = Sqrt(AF * AF – FK * FK) – AN,

where **AF** is the grain outer radius (**AB = AF = AG = AH**),

AF = 5 * PD / 2 + 3 * WEB,

$$FK = DN = PD + WEB,$$

and

$$AN = (PD + WEB) * Sqrt(3).$$

On a similar calculation

$$GM = Sqrt(AG * AG - GL * GL) - AN$$

and

$$HN = AH - AN,$$

in which **GL = MN = DN / 2**. Since sliver 8 is a mirror of 7, and sliver 9 is a mirror of 6, the same geometry can be used again. The entire grain end will contain 12 instances of sliver 6 and also 12 instances of sliver 7. The smaller-than-actual outer edges used in formulating the trapezoidal slivers will mean that the burning outer edge will be slightly smaller than in the real grain sliver, volume will be slightly less than actual, and the simulation will burn out slightly quicker than the original.

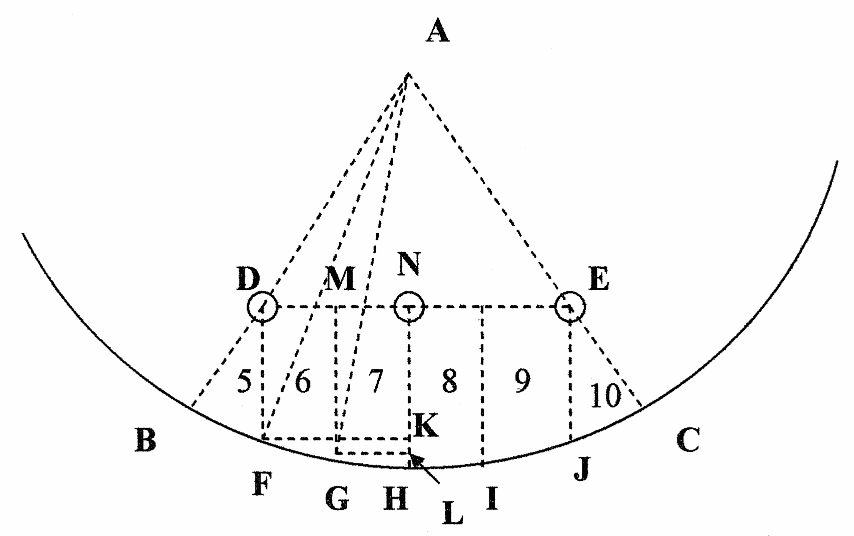


Figure 59. Geometry of 19-perforation cylindrical grain outer slivers.

An input file for the generic grain program with these equations is listed in appendix D, and the output is in appendix E. The output file from an equivalent IBHVG2 computation is in appendix F.

The graph in figure 60 shows the comparison between the "exact" granular surface area from the IBHVG2 form function versus the approximated simulation from the generic grain program. The fit is very good; the only noticeable difference is a slight generic grain over-estimation of surface area in the depth burned region around 0.08 cm.

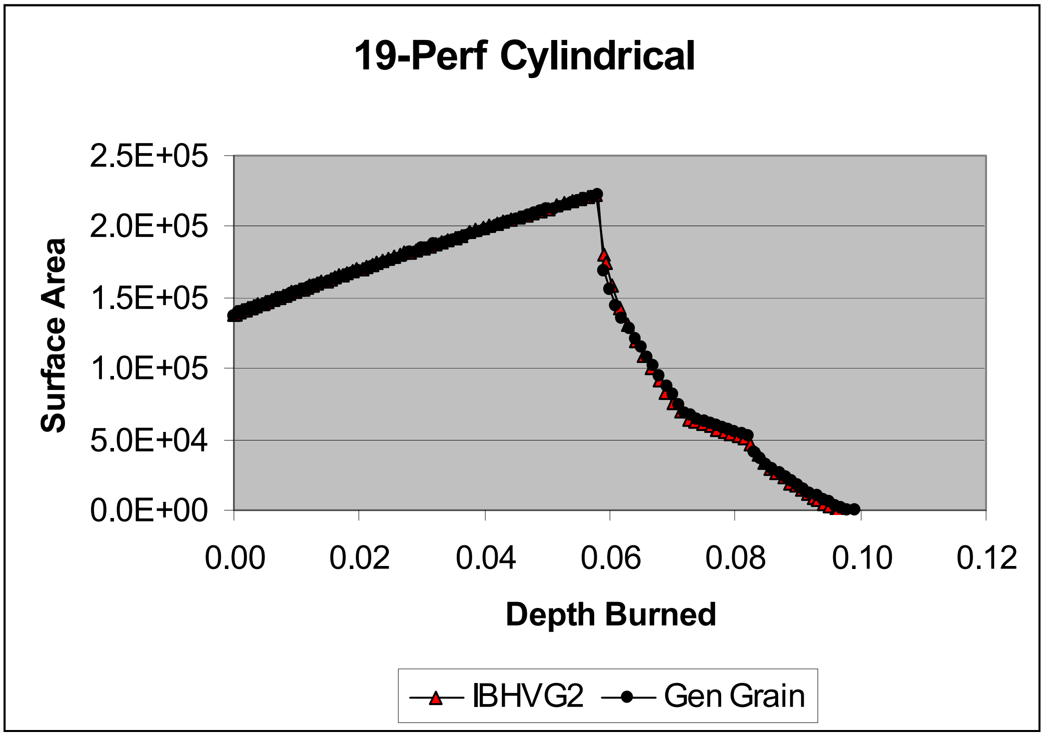


Figure 60. Graphical comparison of output from generic grain and from IBHVG2 with a main charge of 19-perforation cylindrical grains.

8. Using Generic Grain Output in IBHVG2

The interior ballistic program IBHVG2 has an option called the general (GEN) propelling charge that allows an array of depth-burned versus surface area to be used instead of specifying a geometric form function. The program allows as many as 20 data points to be entered; units of measure are meters. By the judicious choice of 20 points, the surface area characteristics are preserved. The best practice is to choose few points where graphed data approach a straight line and many points where curves or breaks are observed.

Appendix G is the result of the new IBHVG2 computation that uses the GEN charge feature. The input deck is copied and printed as the first portion of the output file. Input charge weight will remain the same (22 kg).

The generic grain program must be run with a grain multiplier of 1.0 in order to find the volume of a single grain. Then that volume should be multiplied by the propellant density to find the weight of a single grain. Next, the single-grain weight should be divided into the desired charge weight in order to find the number of grains needed. Then the generic grain program is run again with the computed number of grains to calculate surface area of the total charge.

In this case, the volume of a single grain is 1.288 cc. In the IBHVG2 input file, the density of M30 propellant is 1680.17 kg/m^3, which makes the weight of one grain 2164.05896 cc*kg/m^3. Dividing this weight into total charge weight gives 22 kg/(2164.06 cc*kg/m^3) or 10,166 grains. The generic grain program was run with a grain multiplier of 10,166 to calculate total surface area for a charge of 22 kg. Twenty data points were chosen to be included as part of the IBHVG2 input file; the points are graphed in figure 61 and printed as part of appendix G, which is the new IBHVG2 computation using the GEN charge feature.

Results from the new computation compared to appendix F show a difference of less than 0.3% in muzzle velocity and maximum breech pressure.

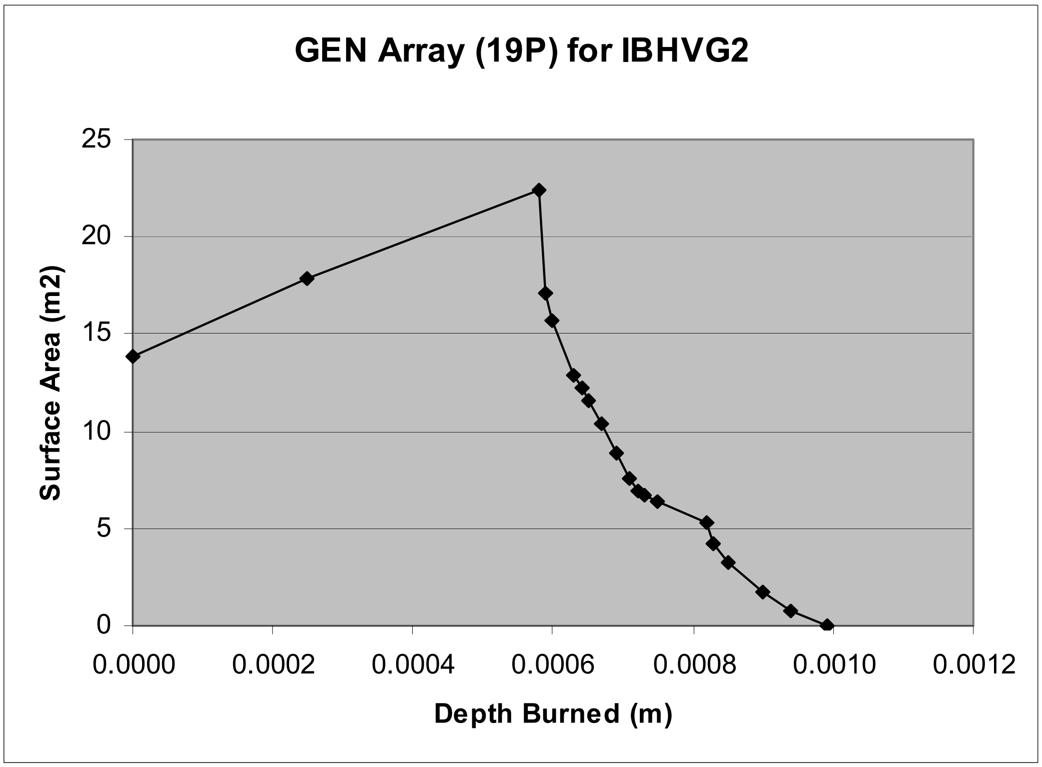


Figure 61. Data to be entered as GEN array in IBHVG2.

9. Sample Novel Grain

Figure 2 shows an end from a theoretical novel extruded grain which could be set between the fins of a six-finned KE projectile. The sides are at a 60-degree angle from the bottom plane; the upper corners are portions of a circle whose radius is greater than the lower corners; the upper surface is a circle segment whose radius is larger than the upper corners. The closest outer surface to the upper two corner perforations and to the top perforation is the same as the web

distance for the inner triangular slivers; the same distance is measured between lower perforation row and bottom surface. The grain is symmetrical from a vertical line centered between the two middle bottom-row perforations and the top perforation. The upper corner surface and upper surface join in a continuous smooth edge.

9.1 Inner Triangular Slivers

By assigning values **R1** to perforation radius, **R2** to upper corner radius, **R3** to the radius of the upper surface, and **W** to web distance, we may find the equations for geometric simulation. The inner triangular slivers are all equal: perforation radii, web length, and angles form 33 congruent triangles (figure 62).

9.2 Outer Slivers

With the outer slivers delineated as in figure 63, the radius of the lower corners is found to be **W + R1**, and the distance between perforation centers is **W + 2 * R1**. Thus slivers 2, 4, and 5 are all equivalent with sides of length **W + R1** and width of **W + 2 * R1**, each with a perforation of radius **R1** at both inner corners. Sliver 1 has the same side lengths but is only half as wide and contains only one inner corner with a perforation. Sliver 3 is a segment of a single-perforation circular grain with inner radius **R1** and outer radius **W + R1**; arc size is **PI / 6** since angle **CDE** is **2 * PI / 3** (contains two angles of equilateral triangles) and angles **CDM** and **EDN** are both size **PI / 2** since lines **DN** and **DM** are perpendicular to lines **DE** and **CD**, respectively.

Figure 64 is an expanded drawing of the upper corner with line **GS** extended to point **Y** so that distance **SY** is equal to **R2**. If one makes the assumption that arc **RST** is completely included in the **R2** circle, then lines **TY** and **RY** are both equal to **R2**. A line drawn from **R** to **T** is bisected at point **A'** and the length of lines **A'T** and **A'R** are both **W + 2 * R1**. Then if the assumption is made that **HT = FR = W + R1**, **A'G** is also equal to **W + R1**. Length **A'S** is computed as

A'S = R2 – Sqrt(R2 * R2 – (W + 2 * R1) * (W + 2 * R1)),

giving the result

GS = W + R1 + A'S.

Angles **QFR** and **THV** are both of size **PI/6** since **GHI** and **EFG** are both size **2 * PI/3** (each contains two angles of equilateral triangles) and angles **IHV**, **GHT**, **GFR**, and **EFQ** are all right angles. Therefore, the slivers drawn as **QFR** and **THV** can be approximated as portions of single-perforated cylindrical grains with inner perforation radius **R1** and outer radius **W + R1**.

Figure 65 shows the outer slivers along the upper edge. The assumptions here are that **HV** and **BJ** are both of length **W + R1** (keeping in line with the proviso that no perforations are closer than **W + R1** to the outer surface of the grain end). Lines **OV**, **OW**, **OX**, and **OB** are all of length **R3**; **IZ** is one-half the distance between perforations, as is **HH'**.

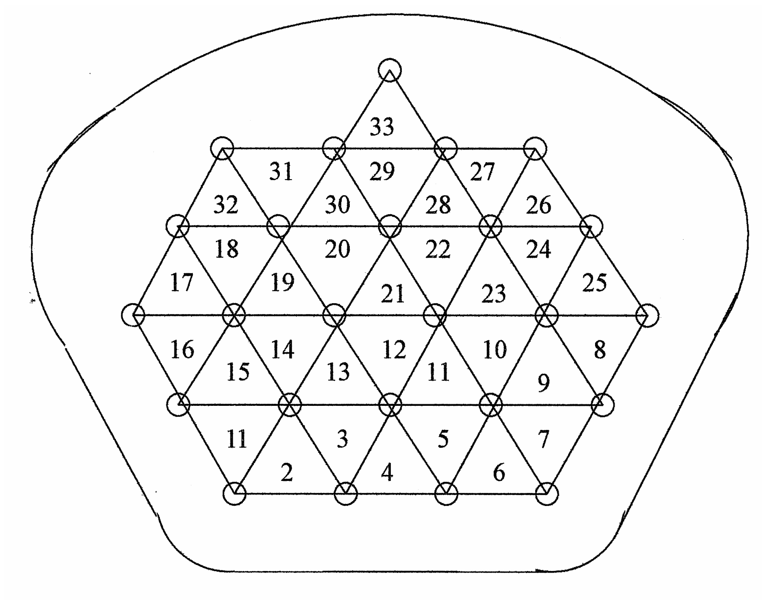


Figure 62. Inner triangular slivers in 25-perforation grain end.

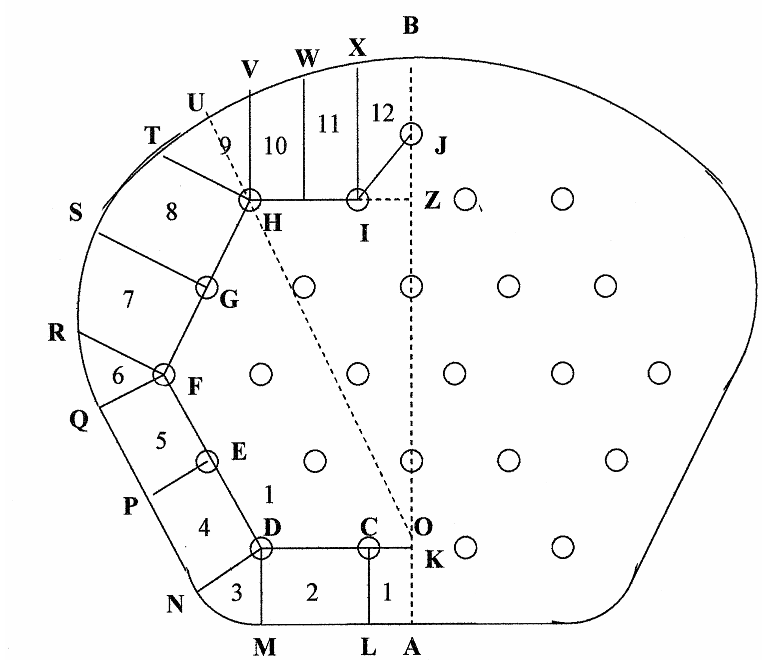


Figure 63. Outer sliver geometry of 25-perforation grain.

Then

$$\mathbf{B'V = 3 * (W + 2 * R1) / 2},$$

$$\mathbf{C'W = W + 2 * R1},$$

and

$$\mathbf{D'X = (W + 2 * R1) / 2}.$$

This allows calculation of the lines

$$BD' = R3 - Sqrt(R3 * R3 - D'X * D'X),$$

$$BC' = R3 - Sqrt(R3 * R3 - C'W * C'W),$$

and

$$BB' = R3 - Sqrt(R3 * R3 - B'V * B'V).$$

The trapezoid sides now can be computed as

$$H'W = HV + BB' - BC',$$

and

$$IX = HV + BB' - BD'.$$

Slivers 10 and 11 are both of trapezoid type 2, while sliver 12 is trapezoid type 1.

The input file for this 25-perforation extruded grain of length **LEN** is shown in parametric terms in figure 66, where the actual line lengths would be substituted for line names when the values of **W**, **R1**, **R2**, **R3**, and **LEN** are known. The assumptions made for finding dimensions of slivers 6 through 12 should result in a small amount of final computational error.

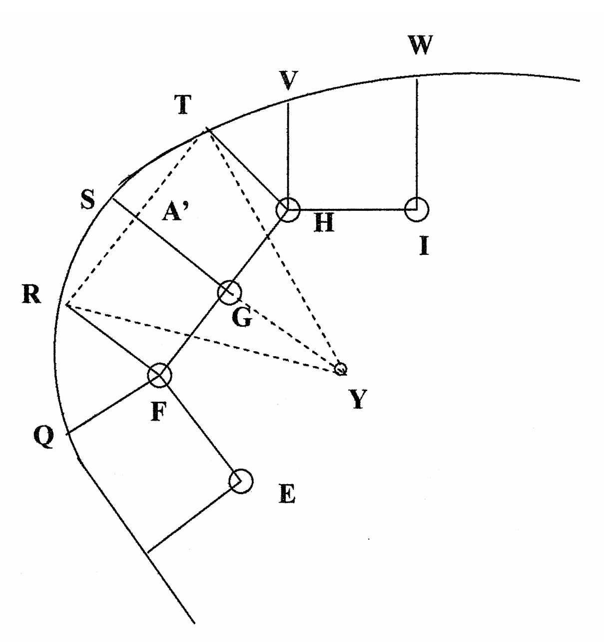


Figure 64. Upper corner outer sliver geometry (25-perf grain).

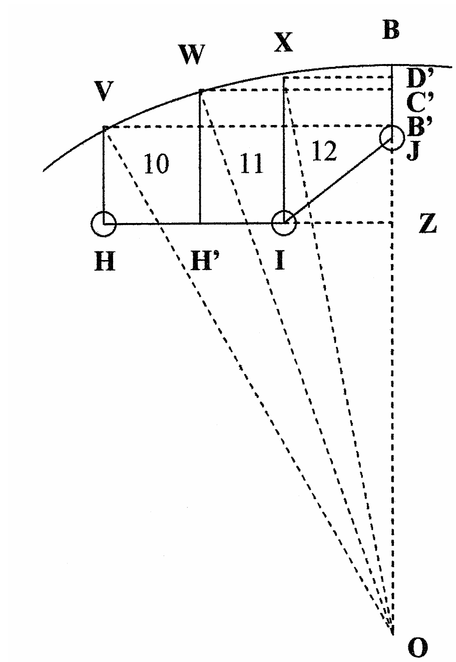


Figure 65. Upper arc slivers (25-perf grain).

```
c  25-perforation extruded grain
c234567890123456789012345678901234567890123456789012345678901234567890
c  sliver 12
c typ nmbr   width     depth    perf      depth      perf     length
  1    2.  W/2 + R1      IX     2 * R1    W + R1    2 * R1      LEN
c  sliver 11
c typ nmbr   width     depth    perf      depth      perf     length
  2    2.  W/2 + R1      IX     2 * R1     H’W        0.0       LEN
c  sliver 10
c typ nmbr   width     depth    perf      depth      perf     length
  2    2.  W/2 + R1     H’W      0.0       HV       2 * R1      LEN
c  slivers 3, 6, and 9
c typ nmbr  perf     o-diam    radians   length
  3    6.    2 * R1  2*(W+R1)   0.5236     LEN
c  slivers 7 and 8
c typ nmbr   width     depth    perf      depth      perf     length
  2    4.  W/2 + R1    W + R1   2 * R1      GS       2 * R1     LEN
c  slivers 2, 4, and 5
c typ nmbr   width     depth    perf      depth      perf     length
  2    6.  W + 2*R1    W + R1   2 * R1    W + R1     2 * R1     LEN
c  sliver 1
c typ nmbr   width     depth    perf      depth      perf     length
  2    2.  W/2 + R1    W + R1   2 * R1    W + R1      0.0       LEN
c  interior equilateral triangle slivers
c typ nmbr  perf      web      length
  4   33.   2 * R1     W         LEN
c dat delta mult
  5  .001    1.
```

Figure 66. Input file for 25-perforation extruded grain.

10. Program Code

The FORTRAN coding for the generic grain program is included in this report as appendix H.

11. Summary

The geometric analysis and process for finding surface area and volume of non-typical extruded propellant grains has been presented with examples of both typical granulations (for testing the mathematics) and unusual grain design (for a processing example). The generic grain program is a useful tool for quick and accurate simulation of previously difficult mathematical representations of experimental propellant grain interior ballistic parameters.

12. References

1. Anderson, R.D.; Fickie, K.D. *IBHVG2 – A User's Guide*; ARL-TR-2928; U.S. Army Ballistics Research Laboratory: Aberdeen Proving Ground, MD, July 1987.

2. Gough, P.S. *The XNOVAKTC Code*; BRL-CR-627; U.S. Army Ballistic Research Laboratory: Aberdeen Proving Ground, MD, February 1990.

3. Lynn, F.R. *Form-Functions for the IBHVG Code*; ARBRL-TR-02438; U.S. Army Armament Research and Development Command, Ballistic Research Laboratory: Aberdeen Proving Ground, MD, November 1982.

Appendix A. Input Deck for 19-Perf Hexagonal Grain

Input deck for Generic Grain program to simulate 19-perforation hexagonal grains.

```
c
c   column 1 - "c" = comment
c
c   type sliver (columns 1-3, right-adjusted integer)
c
c    1 - trapezoidal - outer (burning) edge perpendicular to sides
c    2 - trapezoidal - line between perf centers perpendicular to sides
c    3 - circular - portion of a stick or single-perf sliver
c    4 - triangular - inner triangular slivers
c
c  type 1 trapezoidal
c
c  columns
c    4-10  number of identical slivers, floating-point number
c   11-20  width (shortest distance between parallel sides)
c   21-30  depth from surface to center of perf (short side)
c   31-40  diameter of short-side perf - if no perf, use 0.0
c   41-50  depth from surface to center of perf (long side)
c   51-60  diameter of long-side perf - if no perf, use 0.0
c   61-70  length of sliver
c
c  type 2 trapezoidal
c
c  columns
c    4-10  number of identical slivers, floating-point number
c   11-20  width (shortest distance between parallel sides)
c   21-30  depth from surface to center of perf (short side)
c   31-40  diameter of short-side perf - if no perf, use 0.0
c   41-50  depth from surface to center of perf (long side)
c   51-60  diameter of long-side perf - if no perf, use 0.0
c   61-70  length of sliver
c
c  type 3 circular
c
c  columns
c    4-10 number of identical slivers, floating-point number
c   11-20 diameter of inner perf (if any) - if no perf, use 0.0
c   21-30 diameter of outer arc
c   31-40 arc in radians
c   41-50 length of sliver
c
c  type 4 triangular inner slivers
c
c  columns
c    4-10 number of identical slivers, floating-point number
c   11-20 diameter of corner perfs (three identical)
c   21-30 web distance between perf edges
c   31-40 length of sliver
c
```

```
c  type 5 iteration data
c    4-10 step size for burn iteration
c   11-20 multiplier for output values (defaults to 1.0)
c
c  19-perf hex grain
c
c234567890123456789012345678901234567890123456789012345678901234567890
c typ nmbr   width     depth    perf      depth      perf     length
  1   12.  .182118   .149098    .06604   .149098    .06604    1.70688
c typ nmbr  perf     o-diam    radians   length
  3   6.0   .06604   .298196    1.0472   1.70688
c typ nmbr  perf      web      length
  4   24.   .06604   .116078   1.70688
c dat delta mult
  5  .001  11360.
```

Appendix B. Output File from Generic Grain for 19-Perf Hexagonal Grain

1	1.2000E+01	1.8212E-01	1.4910E-01	6.6040E-02	1.4910E-01	6.6040E-02	1.7069E+00
3	6.0000E+00	6.6040E-02	2.9820E-01	1.0472E+00	1.7069E+00	0.0000E+00	0.0000E+00
4	2.4000E+01	6.6040E-02	1.1608E-01	1.7069E+00	0.0000E+00	0.0000E+00	0.0000E+00
5	1.0000E-03	1.1360E+04	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

z brned	DEPTH BRNED	VOL	SURF	sfe	sfp	sfl
0.00000E+00	0.00000E+00	0.13094E+05	0.15232E+06	0.13506E+01	0.67284E+01	0.53293E+01
0.11704E-01	0.10000E-02	0.12941E+05	0.15419E+06	0.13363E+01	0.69241E+01	0.53123E+01
0.23551E-01	0.20000E-02	0.12785E+05	0.15605E+06	0.13218E+01	0.71192E+01	0.52954E+01
0.35539E-01	0.30000E-02	0.12628E+05	0.15790E+06	0.13072E+01	0.73139E+01	0.52785E+01
0.47669E-01	0.40000E-02	0.12470E+05	0.15974E+06	0.12922E+01	0.75081E+01	0.52616E+01
0.59939E-01	0.50000E-02	0.12309E+05	0.16158E+06	0.12771E+01	0.77019E+01	0.52447E+01
0.72349E-01	0.60000E-02	0.12146E+05	0.16341E+06	0.12617E+01	0.78951E+01	0.52279E+01
0.84899E-01	0.70000E-02	0.11982E+05	0.16523E+06	0.12461E+01	0.80879E+01	0.52111E+01
0.97587E-01	0.80000E-02	0.11816E+05	0.16705E+06	0.12303E+01	0.82802E+01	0.51943E+01
0.11041E+00	0.90000E-02	0.11648E+05	0.16885E+06	0.12142E+01	0.84720E+01	0.51776E+01
0.12338E+00	0.10000E-01	0.11478E+05	0.17065E+06	0.11980E+01	0.86634E+01	0.51608E+01
0.13648E+00	0.11000E-01	0.11307E+05	0.17244E+06	0.11815E+01	0.88543E+01	0.51441E+01
0.14972E+00	0.12000E-01	0.11133E+05	0.17423E+06	0.11647E+01	0.90447E+01	0.51274E+01
0.16309E+00	0.13000E-01	0.10958E+05	0.17600E+06	0.11478E+01	0.92346E+01	0.51108E+01
0.17660E+00	0.14000E-01	0.10781E+05	0.17777E+06	0.11306E+01	0.94240E+01	0.50942E+01
0.19025E+00	0.15000E-01	0.10603E+05	0.17953E+06	0.11132E+01	0.96130E+01	0.50776E+01
0.20402E+00	0.16000E-01	0.10422E+05	0.18128E+06	0.10956E+01	0.98015E+01	0.50610E+01
0.21793E+00	0.17000E-01	0.10240E+05	0.18303E+06	0.10777E+01	0.99895E+01	0.50444E+01
0.23198E+00	0.18000E-01	0.10056E+05	0.18476E+06	0.10596E+01	0.10177E+02	0.50279E+01
0.24616E+00	0.19000E-01	0.98707E+04	0.18649E+06	0.10413E+01	0.10364E+02	0.50114E+01
0.26047E+00	0.20000E-01	0.96833E+04	0.18822E+06	0.10228E+01	0.10551E+02	0.49949E+01
0.27491E+00	0.21000E-01	0.94942E+04	0.18993E+06	0.10040E+01	0.10737E+02	0.49785E+01
0.28948E+00	0.22000E-01	0.93034E+04	0.19164E+06	0.98500E+00	0.10922E+02	0.49620E+01
0.30418E+00	0.23000E-01	0.91110E+04	0.19333E+06	0.96578E+00	0.11107E+02	0.49456E+01
0.31901E+00	0.24000E-01	0.89168E+04	0.19503E+06	0.94633E+00	0.11292E+02	0.49292E+01
0.33397E+00	0.25000E-01	0.87209E+04	0.19671E+06	0.92666E+00	0.11476E+02	0.49129E+01
0.34905E+00	0.26000E-01	0.85234E+04	0.19838E+06	0.90677E+00	0.11660E+02	0.48966E+01
0.36427E+00	0.27000E-01	0.83241E+04	0.20005E+06	0.88665E+00	0.11843E+02	0.48803E+01
0.37961E+00	0.28000E-01	0.81233E+04	0.20171E+06	0.86630E+00	0.12026E+02	0.48640E+01
0.39508E+00	0.29000E-01	0.79207E+04	0.20336E+06	0.84572E+00	0.12208E+02	0.48477E+01
0.41067E+00	0.30000E-01	0.77165E+04	0.20501E+06	0.82492E+00	0.12390E+02	0.48315E+01
0.42639E+00	0.31000E-01	0.75107E+04	0.20665E+06	0.80389E+00	0.12571E+02	0.48153E+01
0.44223E+00	0.32000E-01	0.73032E+04	0.20827E+06	0.78264E+00	0.12752E+02	0.47991E+01
0.45820E+00	0.33000E-01	0.70942E+04	0.20990E+06	0.76116E+00	0.12933E+02	0.47830E+01
0.47430E+00	0.34000E-01	0.68835E+04	0.21151E+06	0.73945E+00	0.13112E+02	0.47668E+01
0.49051E+00	0.35000E-01	0.66711E+04	0.21312E+06	0.71752E+00	0.13292E+02	0.47507E+01
0.50685E+00	0.36000E-01	0.64572E+04	0.21471E+06	0.69536E+00	0.13471E+02	0.47347E+01
0.52331E+00	0.37000E-01	0.62417E+04	0.21630E+06	0.67298E+00	0.13649E+02	0.47186E+01
0.53989E+00	0.38000E-01	0.60246E+04	0.21789E+06	0.65037E+00	0.13827E+02	0.47026E+01
0.55659E+00	0.39000E-01	0.58060E+04	0.21946E+06	0.62753E+00	0.14005E+02	0.46866E+01
0.57341E+00	0.40000E-01	0.55857E+04	0.22103E+06	0.60447E+00	0.14182E+02	0.46706E+01
0.59035E+00	0.41000E-01	0.53639E+04	0.22259E+06	0.58118E+00	0.14358E+02	0.46547E+01
0.60741E+00	0.42000E-01	0.51405E+04	0.22414E+06	0.55766E+00	0.14534E+02	0.46387E+01
0.62458E+00	0.43000E-01	0.49156E+04	0.22569E+06	0.53392E+00	0.14710E+02	0.46228E+01
0.64188E+00	0.44000E-01	0.46892E+04	0.22722E+06	0.50996E+00	0.14885E+02	0.46070E+01
0.65929E+00	0.45000E-01	0.44612E+04	0.22875E+06	0.48576E+00	0.15060E+02	0.45911E+01
0.67682E+00	0.46000E-01	0.42317E+04	0.23027E+06	0.46134E+00	0.15234E+02	0.45753E+01
0.69446E+00	0.47000E-01	0.40006E+04	0.23179E+06	0.43669E+00	0.15408E+02	0.45595E+01
0.71222E+00	0.48000E-01	0.37681E+04	0.23329E+06	0.41182E+00	0.15581E+02	0.45437E+01
0.73010E+00	0.49000E-01	0.35340E+04	0.23479E+06	0.38672E+00	0.15753E+02	0.45280E+01
0.74809E+00	0.50000E-01	0.32985E+04	0.23628E+06	0.36140E+00	0.15926E+02	0.45122E+01
0.76619E+00	0.51000E-01	0.30615E+04	0.23776E+06	0.33585E+00	0.16098E+02	0.44965E+01

0.78440E+00	0.52000E-01	0.28230E+04	0.23924E+06	0.31007E+00	0.16269E+02	0.44809E+01
0.80273E+00	0.53000E-01	0.25830E+04	0.24071E+06	0.28407E+00	0.16440E+02	0.44652E+01
0.82117E+00	0.54000E-01	0.23416E+04	0.24217E+06	0.25784E+00	0.16610E+02	0.44496E+01
0.83972E+00	0.55000E-01	0.20987E+04	0.24362E+06	0.23138E+00	0.16780E+02	0.44340E+01
0.85838E+00	0.56000E-01	0.18544E+04	0.24506E+06	0.20470E+00	0.16949E+02	0.44184E+01
0.87715E+00	0.57000E-01	0.16086E+04	0.24650E+06	0.17779E+00	0.17118E+02	0.44029E+01
0.89603E+00	0.58000E-01	0.13614E+04	0.24793E+06	0.15066E+00	0.17287E+02	0.43873E+01
0.91074E+00	0.59000E-01	0.11688E+04	0.17214E+06	0.12951E+00	0.12264E+02	0.27589E+01
0.92295E+00	0.60000E-01	0.10089E+04	0.14908E+06	0.11193E+00	0.10561E+02	0.24501E+01
0.93365E+00	0.61000E-01	0.86881E+03	0.13164E+06	0.96512E-01	0.92773E+01	0.22145E+01
0.94313E+00	0.62000E-01	0.74464E+03	0.11705E+06	0.82823E-01	0.82045E+01	0.20163E+01
0.95157E+00	0.63000E-01	0.63412E+03	0.10424E+06	0.70619E-01	0.72637E+01	0.18421E+01
0.95908E+00	0.64000E-01	0.53574E+03	0.92691E+05	0.59739E-01	0.64148E+01	0.16848E+01
0.96575E+00	0.65000E-01	0.44842E+03	0.82078E+05	0.50066E-01	0.56346E+01	0.15405E+01
0.97164E+00	0.66000E-01	0.37134E+03	0.72201E+05	0.41512E-01	0.49078E+01	0.14064E+01
0.97680E+00	0.67000E-01	0.30382E+03	0.62921E+05	0.34008E-01	0.42240E+01	0.12808E+01
0.98126E+00	0.68000E-01	0.24533E+03	0.54134E+05	0.27496E-01	0.35757E+01	0.11621E+01
0.98508E+00	0.69000E-01	0.19541E+03	0.45767E+05	0.21929E-01	0.29573E+01	0.10495E+01
0.98826E+00	0.70000E-01	0.15368E+03	0.37759E+05	0.17268E-01	0.23644E+01	0.94217E+00
0.99085E+00	0.71000E-01	0.11979E+03	0.30064E+05	0.13477E-01	0.17936E+01	0.83942E+00
0.99286E+00	0.72000E-01	0.93459E+02	0.22646E+05	0.10528E-01	0.12422E+01	0.74077E+00
0.99444E+00	0.73000E-01	0.72743E+02	0.19290E+05	0.82048E-02	0.10441E+01	0.64581E+00
0.99581E+00	0.74000E-01	0.54812E+02	0.16583E+05	0.61904E-02	0.89942E+00	0.55417E+00
0.99698E+00	0.75000E-01	0.39549E+02	0.13957E+05	0.44723E-02	0.75855E+00	0.46557E+00
0.99795E+00	0.76000E-01	0.26874E+02	0.11405E+05	0.30429E-02	0.62113E+00	0.37974E+00
0.99872E+00	0.77000E-01	0.16717E+02	0.89199E+04	0.18953E-02	0.48683E+00	0.29648E+00
0.99931E+00	0.78000E-01	0.90136E+01	0.64976E+04	0.10232E-02	0.35538E+00	0.21557E+00
0.99972E+00	0.79000E-01	0.37025E+01	0.41328E+04	0.42086E-03	0.22651E+00	0.13687E+00
0.99994E+00	0.80000E-01	0.73020E+00	0.18215E+04	0.83107E-04	0.10004E+00	0.60216E-01
0.10000E+01	0.81000E-01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00

Appendix C. IBHVG2 Output Using 19-Perf Hexagonal Grains

Output from IBHVG2 using 19-perforation hexagonal grains as major propellant.

```
  ERRTOL=  1.1920929E-07
1                                          IBHVG2.506     DATE             TIME

0 CARD   1 --> $COMM
  CARD   2 -->          FROM IBHVG2 BENCHMARK TEST CASE 1
  CARD   3 --> $INFO
  CARD   4 -->         POPT=1,2,1,0   $  ECHO INPUT LINES, PRINT TRAJECTORY + SUMMARY
  CARD   5 -->         RUN='M30 19-PERF HEX - LOT UNKNOWN'
  CARD   6 -->         GRAD = 3       $ INVOKE CHAMBRAGE GRADIENT
  CARD   7 --> $TDIS
  CARD   8 -->         SHOW='TIME' REMK='TIME'
  CARD   9 --> $TDIS
  CARD  10 -->         SHOW='TRAV' REMK='TRAV'
  CARD  11 --> $TDIS
  CARD  12 -->         SHOW='Z(2)' REMK='FRAC BRND'
  CARD  13 --> $TDIS
  CARD  14 -->         SHOW='DB-P(2)' REMK='DB BRND CM' MULT=100.
  CARD  15 --> $TDIS
  CARD  16 -->         SHOW='SRF(2)' REMK='SRF (CM2)' MULT=10000.
  CARD  17 --> $GUN
  CARD  18 -->         NAME='HARP GUN'   $ SMOOTHBORE
  CARD  19 -->         CHAM=0.072   GRVE=.1852168   LAND=.1852168
  CARD  20 -->         TRAV=3.0  TWST=99
  CARD  21 -->         CPTS = 3  DIST = 0.0,    1.3900,   1.5000
  CARD  22 -->                   DIAM = 0.250,  0.250,     0.1852168
  CARD  23 --> $COMMENT
  CARD  24 -->         PRIMER IS ASSUMED ALL BURNED AT TIME=0.0
  CARD  25 -->         IGNITER CHARGE IS PROPELLANT 1
  CARD  26 -->         MAIN CHARGE IS PROPELLANT 2
  CARD  27 --> $PRIM
  CARD  28 -->         NAME='BLK POWDER'  CHWT=.006985322
  CARD  29 -->         GAMA=1.25   TEMP=2000   FORC=286950.  $ FORC=J/KG
  CARD  30 -->         COV=.001083818                        $ COV=M3/KG
  CARD  31 --> $PROP
  CARD  32 -->         NAME='BLK POWDER'  GRAN='CORD' CHWT=.6803885
  CARD  33 -->         LEN=.0050292 DIAM=.0024892 RHO=1660.794  TEMP=2000
  CARD  34 -->         GAMA=1.25    FORC=286950.  COV=.001264455
  CARD  35 -->         ALPH=0.0     BETA=0.508
  CARD  36 -->            $ BETA(M/S)=BETA(PSI)*0.0254 WHEN ALPH=0.0
  CARD  37 --> $PROP
  CARD  38 -->         NAME='M30 LOT UNKNOWN'     GRAN='19HX'  CHWT=22.
  CARD  39 -->         TEMP=3012    RHO=1680.17                    $ DENSITY=KG/M3
  CARD  40 -->         LEN=.01706880 PD=.0006604    WEB=.00116078  $ LENGTH=METERS
  CARD  41 -->         GAMA=1.2441  FORC=1075693. COV=.001027496   $ FORC=J/KG COV=M3/KG
  CARD  42 -->         NTBL=4   PR4L=41.368542,68.94757,82.737084,275.79028    $ PRES=MPA
  CARD  43 -->                  BR4L=.0508,.065024,.06985,.1508760 $ RATE=M/S
  CARD  44 --> $PROJ
  CARD  45 -->         NAME='PLASTIC LAB SABOT' PRWT=23.58576
  CARD  46 --> $RESI
  CARD  47 -->         NPTS=4
  CARD  48 -->         TRAV=0,    .00762,   .07620,   15.24               $ DIST=METERS
  CARD  49 -->         PRES=.6894757, 27.579028,   12.4105626,   5.5158   $ PRES=MPA
  CARD  50 --> $END
1M30 19-PERF HEX - LOT UNKNOWN                         IBHVG2.506     DATE             TIME

0  CHAMBER DESCRIPTION      INTEGRATED VOLUME    0.0723527

          POSITION     DIAMETER
            (M)          (M)
    1     0.0000000    0.2500000
```

```
   2     1.3900000    0.2500000
   3     1.5000000    0.1852168
 **WARNING** CHAMBER VOLUME OVERRIDDEN BY COMPUTED VALUE
```



```
 ------------
 - GUN TUBE -
 ------------

TYPE: HARP GUN                    CHAMBER VOLUME (M3):  0.07235    TRAVEL (M):          3.00000
GROOVE DIAMETER (M):    0.18522   LAND DIAMETER (M):    0.18522    GROOVE/LAND RATIO (-):  0.000
TWIST (CALS/TURN):      99.0      BORE AREA (M2):       0.02694    HEAT-LOSS OPTION:    1
 **WARNING: GROOVE/LAND RATIO .LE. 0., GUN TUBE IS ASSUMED TO BE SMOOTH-BORE OF DIAMETER 0.18522
SHELL THICKNESS (M):    0.000102  SHELL CP (J/KG-K):   460.3163
SHELL DENSITY (KG/M3):  7861.0918
INITIAL SHELL TEMP (K): 293.      AIR H0 (W/M**2-K):    11.3482

 --------------
 - PROJECTILE -
 --------------

   TYPE: PLASTIC LAB SABOT        TOTAL WEIGHT (KG):    23.586       WEIGHT PREDICTOR OPTION: 0

 --------------
 - RESISTANCE -
 --------------

AIR RESISTANCE OPTION:   1        TUBE GAS INITIAL PRES (MPA) 0.000  WALL HEATING FRACTION:
0.000
RESISTIVE PRESSURE MULT INDEX: 3  RESISTIVE FACTOR           1.000  FRICTION TABLE LENGTH:   4

 I   TRAVEL (M)  PRESSURE (MPA)   I  TRAVEL (M)  PRESSURE (MPA)   I  TRAVEL (M)  PRESSURE (MPA)

 1    0.000         0.689         3    0.076        12.411        4    15.240       5.516
 2    0.008        27.579

 -----------
 - GENERAL -
 -----------

MAX TIME STEP (S):     0.000100    PRINT STEP (S):    0.000000    MAX RELATIVE ERROR (-):
0.00200
PRINT OPTIONS:          1 2 1 0 1 1     STORE OPTION:   0       CONSTANT-PRESSURE OPTION:   0
GRADIENT MODEL: CHAMBRAGE

 ----------
 - RECOIL -
 ----------

RECOIL OPTION:       0       TYPE:                               RECOILING WEIGHT (KG):     0.

 ----------
 - PRIMER -
 ----------

TYPE: BLK POWDER                    GAMMA (-):         1.2500       FORCE (J/KG):        286950.
COVOLUME (M3/KG):     1.0838E-03    FLAME TEMP (K):   2000.0        WEIGHT (KG):         0.006985
```



```
 ------------
 - CHARGE 1 -
 ------------

TYPE: BLK POWDER                    GRAINS:           16739.     CORD     WEIGHT (KG):   0.6804
EROSIVE COEFF (-):     0.000000     CHARGE IGN CODE:      0      CHARGE IGN AT (S): 0.00000E+00
GRAIN LENGTH (M):      0.005029     GRAIN DIAMETER (M):   0.002489
```

```
PROPERTIES AT LAYER BOUNDARIES OF END SURFACES     PROPERTIES AT LAYER BOUNDARIES OF LAT SURFACES
                        1ST     2ND     3RD     4TH         1ST     2ND     3RD     4TH
AT DEPTH (M):          ------ ------  ------  0.00000     ------  ------  ------  0.00000
ADJACENT LAYER WT %:   ------ ------  ------  100.000     ------  ------  ------  100.000
DENSITY (KG/M3):       ------ ------  ------ 1660.794     ------  ------  ------ 1660.794
GAMMA (-):             ------ ------  ------   1.2500     ------  ------  ------   1.2500
FORCE (J/KG):          ------ ------  ------  286950.     ------  ------  ------  286950.
COVOLUME (M3/KG):      ------ ------  ------ 1.2645E-03   ------  ------  ------ 1.2645E-03
FLAME TEMP (K):        ------ ------  ------   2000.0     ------  ------  ------   2000.0
BURNING RATE EXPS:     ------ ------  ------   0.0000     ------  ------  ------   0.0000
BURNING RATE COEFFS:   ------ ------  ------   0.5080     ------  ------  ------   0.5080

1M30 19-PERF HEX - LOT UNKNOWN                         IBHVG2.506     DATE             TIME


 ------------
 - CHARGE 2 -
 ------------

TYPE: M30 LOT UNKNOWN            GRAINS:           11360.     19HX     WEIGHT (KG):   22.0000
EROSIVE COEFF (-):   0.000000   CHARGE IGN CODE:      0       CHARGE IGN AT (S):  0.00000E+00
GRAIN LENGTH (M):    0.017069   GRAIN DIAMETER (M): 0.010267   PERF DIAMETER (M):     0.000660
INNER WEB (M):       0.001161   MIDDLE WEB (M):     0.001161   OUTER WEB (M):         0.001161

PROPERTIES AT LAYER BOUNDARIES OF PERF SURFACES    PROPERTIES AT LAYER BOUNDARIES OF END SURFACES
                        1ST     2ND     3RD     4TH         1ST     2ND     3RD     4TH
AT DEPTH (M):         ------  ------  ------  0.00000     ------  ------  ------  0.00000
ADJACENT LAYER WT %:  ------  ------  ------  100.000     ------  ------  ------  100.000
DENSITY (KG/M3):      ------  ------  ------ 1680.170     ------  ------  ------ 1680.170
GAMMA (-):            ------  ------  ------   1.2441     ------  ------  ------   1.2441
FORCE (J/KG):         ------  ------  ------ 1075693.     ------  ------  ------ 1075693.
COVOLUME (M3/KG):     ------  ------  ------ 1.0275E-03   ------  ------  ------  1.0275E-03
FLAME TEMP (K):       ------  ------  ------   3012.0     ------  ------  ------   3012.0
MEAN PRESSURES (MPA): ------  ------  ------   41.369     ------  ------  ------   41.369
MEAN PRESSURES (MPA): ------  ------  ------   68.948     ------  ------  ------   68.948
MEAN PRESSURES (MPA): ------  ------  ------   82.737     ------  ------  ------   82.737
MEAN PRESSURES (MPA): ------  ------  ------  275.790     ------  ------  ------  275.790
BURNING RATES (M/S):  ------  ------  ------  0.05080     ------  ------  ------  0.05080
BURNING RATES (M/S):  ------  ------  ------  0.06502     ------  ------  ------  0.06502
BURNING RATES (M/S):  ------  ------  ------  0.06985     ------  ------  ------  0.06985
BURNING RATES (M/S):  ------  ------  ------  0.15088     ------  ------  ------  0.15088

                         PROPERTIES AT LAYER BOUNDARIES OF  LAT SURFACES
                              1ST         2ND         3RD         4TH

   AT DEPTH (M):             ------      ------      ------     0.00000
   ADJACENT LAYER WT %:      ------      ------      ------     100.000
   DENSITY (KG/M3):          ------      ------      ------    1680.170
   GAMMA (-):                ------      ------      ------      1.2441
   FORCE (J/KG):             ------      ------      ------    1075693.
   COVOLUME (M3/KG):         ------      ------      ------  1.0275E-03
   FLAME TEMP (K):           ------      ------      ------      3012.0
   MEAN PRESSURES (MPA):     ------      ------      ------      41.369
   MEAN PRESSURES (MPA):     ------      ------      ------      68.948
   MEAN PRESSURES (MPA):     ------      ------      ------      82.737
   MEAN PRESSURES (MPA):     ------      ------      ------     275.790
   BURNING RATES (M/S):      ------      ------      ------     0.05080
   BURNING RATES (M/S):      ------      ------      ------     0.06502
   BURNING RATES (M/S):      ------      ------      ------     0.06985
   BURNING RATES (M/S):      ------      ------      ------     0.15088
1M30 19-PERF HEX - LOT UNKNOWN                         IBHVG2.506     DATE             TIME

      TRAJECTORY VARIABLES: / 1/  TRAJ 1  TIME          TIME
                            / 2/  TRAJ 1  TRAV          TRAV
                            / 3/  TRAJ 1  Z(2)          FRAC BRND
                            / 4/  TRAJ 1  DB-P(2)       DB BRND CM
                            / 5/  TRAJ 1  SRF(2)        SRF (CM2)

    / 1/        / 2/        / 3/        / 4/        / 5/
0 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.15232E+06
  0.10000E+00 0.00000E+00 0.50947E-03 0.43784E-04 0.15240E+06
```

```
  0.11932     0.00000E+00 0.66045E-03 0.56754E-04 0.15243E+06
 SHOT-START PRESSURE ACHIEVED
  0.20000     0.60256E-06 0.14330E-02 0.12310E-03 0.15255E+06
  0.30000     0.70208E-05 0.26725E-02 0.22941E-03 0.15275E+06
  0.40000     0.27101E-04 0.41898E-02 0.35938E-03 0.15299E+06
  0.50000     0.69167E-04 0.59632E-02 0.51101E-03 0.15328E+06
  0.60000     0.14163E-03 0.79784E-02 0.68299E-03 0.15360E+06
  0.70000     0.25261E-03 0.10226E-01 0.87434E-03 0.15395E+06
  0.80000     0.40966E-03 0.12698E-01 0.10843E-02 0.15434E+06
  0.90000     0.61939E-03 0.15390E-01 0.13124E-02 0.15477E+06
  1.00000     0.88729E-03 0.18298E-01 0.15580E-02 0.15523E+06
   1.1000     0.12175E-02 0.21419E-01 0.18209E-02 0.15572E+06
   1.2000     0.16125E-02 0.24751E-01 0.21006E-02 0.15623E+06
   1.3000     0.20735E-02 0.28294E-01 0.23970E-02 0.15678E+06
   1.4000     0.25996E-02 0.32046E-01 0.27098E-02 0.15736E+06
   1.5000     0.31888E-02 0.36008E-01 0.30389E-02 0.15797E+06
   1.6000     0.38370E-02 0.40180E-01 0.33840E-02 0.15861E+06
   1.7000     0.45393E-02 0.44563E-01 0.37451E-02 0.15928E+06
   1.8000     0.52892E-02 0.49158E-01 0.41220E-02 0.15997E+06
   1.9000     0.60795E-02 0.53967E-01 0.45148E-02 0.16069E+06
   2.0000     0.69022E-02 0.58992E-01 0.49232E-02 0.16144E+06
   2.1000     0.77490E-02 0.64234E-01 0.53474E-02 0.16222E+06
   2.2000     0.86201E-02 0.69697E-01 0.57872E-02 0.16302E+06
   2.3000     0.95373E-02 0.75383E-01 0.62427E-02 0.16386E+06
   2.4000     0.10527E-01 0.81294E-01 0.67139E-02 0.16471E+06
   2.4500     0.11057E-01 0.84336E-01 0.69553E-02 0.16515E+06
 PROPELLANT 1 BURNED OUT
   2.5000     0.11616E-01 0.87435E-01 0.72007E-02 0.16560E+06
   2.6000     0.12833E-01 0.93807E-01 0.77032E-02 0.16651E+06
   2.7000     0.14207E-01 0.10042     0.82215E-02 0.16745E+06
   2.8000     0.15771E-01 0.10727     0.87555E-02 0.16841E+06
   2.9000     0.17554E-01 0.11436     0.93054E-02 0.16941E+06
   3.0000     0.19593E-01 0.12170     0.98712E-02 0.17042E+06
   3.1000     0.21920E-01 0.12929     0.10453E-01 0.17147E+06
   3.2000     0.24575E-01 0.13714     0.11050E-01 0.17254E+06
   3.3000     0.27594E-01 0.14526     0.11664E-01 0.17363E+06
   3.4000     0.31018E-01 0.15363     0.12294E-01 0.17475E+06
   3.5000     0.34889E-01 0.16227     0.12939E-01 0.17590E+06
   3.6000     0.39250E-01 0.17116     0.13598E-01 0.17706E+06
   3.7000     0.44147E-01 0.18027     0.14270E-01 0.17825E+06
   3.8000     0.49626E-01 0.18963     0.14955E-01 0.17945E+06
   3.9000     0.55736E-01 0.19922     0.15653E-01 0.18068E+06
   4.0000     0.62527E-01 0.20915     0.16369E-01 0.18193E+06
   4.1000     0.70051E-01 0.21942     0.17106E-01 0.18321E+06
   4.2000     0.78364E-01 0.23006     0.17864E-01 0.18453E+06
   4.3000     0.87515E-01 0.24107     0.18642E-01 0.18588E+06
   4.4000     0.97545E-01 0.25246     0.19442E-01 0.18726E+06
   4.5000     0.10849     0.26423     0.20262E-01 0.18867E+06
1M30 19-PERF HEX - LOT UNKNOWN                        IBHVG2.506     DATE             TIME

      TRAJECTORY VARIABLES: / 1/  TRAJ 1  TIME          TIME
                            / 2/  TRAJ 1  TRAV          TRAV
                            / 3/  TRAJ 1  Z(2)          FRAC BRND
                            / 4/  TRAJ 1  DB-P(2)       DB BRND CM
                            / 5/  TRAJ 1  SRF(2)        SRF (CM2)

    / 1/        / 2/        / 3/        / 4/        / 5/
0  4.6000     0.12040     0.27640     0.21103E-01 0.19011E+06
   4.7000     0.13330     0.28896     0.21965E-01 0.19158E+06
   4.8000     0.14723     0.30192     0.22847E-01 0.19308E+06
   4.9000     0.16224     0.31530     0.23751E-01 0.19461E+06
   5.0000     0.17837     0.32910     0.24675E-01 0.19616E+06
   5.1000     0.19565     0.34331     0.25620E-01 0.19775E+06
   5.2000     0.21412     0.35795     0.26586E-01 0.19936E+06
   5.3000     0.23383     0.37303     0.27572E-01 0.20100E+06
   5.4000     0.25480     0.38853     0.28578E-01 0.20267E+06
   5.5000     0.27709     0.40448     0.29604E-01 0.20436E+06
   5.6000     0.30072     0.42086     0.30649E-01 0.20607E+06
   5.7000     0.32573     0.43769     0.31714E-01 0.20781E+06
   5.8000     0.35216     0.45496     0.32798E-01 0.20957E+06
   5.9000     0.38005     0.47268     0.33900E-01 0.21135E+06
```

```
   6.0000     0.40942     0.49084     0.35020E-01 0.21315E+06
   6.1000     0.44032     0.50945     0.36158E-01 0.21497E+06
   6.2000     0.47277     0.52849     0.37314E-01 0.21680E+06
   6.3000     0.50681     0.54798     0.38486E-01 0.21866E+06
   6.4000     0.54246     0.56791     0.39674E-01 0.22052E+06
   6.5000     0.57977     0.58828     0.40878E-01 0.22240E+06
   6.6000     0.61874     0.60908     0.42098E-01 0.22430E+06
   6.7000     0.65943     0.63030     0.43331E-01 0.22620E+06
   6.8000     0.70184     0.65195     0.44579E-01 0.22811E+06
   6.9000     0.74600     0.67402     0.45841E-01 0.23003E+06
   7.0000     0.79194     0.69651     0.47115E-01 0.23196E+06
   7.1000     0.83969     0.71940     0.48402E-01 0.23390E+06
   7.2000     0.88925     0.74268     0.49700E-01 0.23584E+06
   7.3000     0.94066     0.76637     0.51010E-01 0.23778E+06
   7.4000     0.99394     0.79043     0.52330E-01 0.23973E+06
   7.5000      1.0491     0.81487     0.53659E-01 0.24167E+06
   7.6000      1.1061     0.83968     0.54998E-01 0.24362E+06
   7.7000      1.1651     0.86485     0.56346E-01 0.24556E+06
   7.8000      1.2260     0.89038     0.57701E-01 0.24750E+06
   7.8648      1.2665     0.90461     0.58582E-01 0.18563E+06
 LOCAL PRESSURE MAX DETECTED
   7.9000      1.2888     0.91112     0.59062E-01 0.17043E+06
   8.0000      1.3536     0.92718     0.60420E-01 0.14130E+06
   8.1000      1.4203     0.94064     0.61772E-01 0.12019E+06
   8.2000      1.4889     0.95205     0.63115E-01 0.10285E+06
   8.3000      1.5594     0.96174     0.64447E-01  87846.
   8.4000      1.6317     0.96990     0.65765E-01  74463.
   8.5000      1.7058     0.97670     0.67069E-01  62302.
   8.6000      1.7817     0.98227     0.68356E-01  51109.
   8.7000      1.8593     0.98672     0.69627E-01  40709.
   8.8000      1.9386     0.99014     0.70879E-01  30978.
   8.9000      2.0196     0.99263     0.72113E-01  21822.
   9.0000      2.1021     0.99449     0.73328E-01  18393.
   9.1000      2.1862     0.99602     0.74524E-01  15197.
   9.2000      2.2718     0.99725     0.75701E-01  12161.
   9.3000      2.3588     0.99820     0.76858E-01  9267.7
1M30 19-PERF HEX - LOT UNKNOWN                        IBHVG2.506     DATE             TIME

      TRAJECTORY VARIABLES: / 1/  TRAJ 1  TIME          TIME
                            / 2/  TRAJ 1  TRAV          TRAV
                            / 3/  TRAJ 1  Z(2)          FRAC BRND
                            / 4/  TRAJ 1  DB-P(2)       DB BRND CM
                            / 5/  TRAJ 1  SRF(2)        SRF (CM2)

    / 1/        / 2/        / 3/        / 4/        / 5/
0  9.4000      2.4473     0.99888     0.77997E-01  6503.7
   9.5000      2.5372     0.99932     0.79118E-01  3857.7
   9.6000      2.6284     0.99954     0.80220E-01  1320.2
   9.6537      2.6779      1.0000     0.80804E-01 0.00000E+00
 PROPELLANT 2 BURNED OUT
   9.7000      2.7210      1.0000     0.80804E-01 0.00000E+00
   9.8000      2.8148      1.0000     0.80804E-01 0.00000E+00
   9.9000      2.9098      1.0000     0.80804E-01 0.00000E+00
   9.9937      3.0000      1.0000     0.80804E-01 0.00000E+00
 PROJECTILE EXIT
1M30 19-PERF HEX - LOT UNKNOWN                        IBHVG2.506     DATE             TIME


 CONDITIONS AT:           PMAX   MUZZLE

 TIME (MS):              7.865    9.994
 TRAVEL (M):            1.2665   3.0000
 VELOCITY (M/S)         631.24   967.66
 ACCELERATION (G):      19823.   11947.
 BREECH PRESS (MPA): 252.3113 167.4110
 MEAN PRESS (MPA):   234.7576 150.5017
 BASE PRESS (MPA):   182.7053 115.0800
 MEAN TEMP (K):          2734.    2455.
 Z CHARGE 1 (-):         1.000    1.000
 Z CHARGE 2 (-):         0.905    1.000
```

ENERGY BALANCE SUMMARY	JOULE	%
TOTAL CHEMICAL:	97696392.	100.00
(1) INTERNAL GAS:	79955904.	81.84
(2) WORK AND LOSSES:	17740488.	18.16
(A) PROJECTILE KINETIC:	11042489.	11.30
(B) GAS KINETIC:	3294224.	3.37
(C) PROJECTILE ROTATIONAL:	5560.	0.01
(D) FRICTIONAL WORK TO TUBE:	0.	0.00
(E) OTHER FRICTIONAL WORK:	965149.	0.99
(F) WORK DONE AGAINST AIR:	61855.	0.06
(G) HEAT CONVECTED TO BORE:	2371210.	2.43
(H) RECOIL ENERGY:	0.	0.00

LOADING DENSITY (KG/M3):	313.566
CHARGE WT/PROJECTILE WT:	0.962
PIEZOMETRIC EFFICIENCY:	0.541
EXPANSION RATIO:	2.117

Appendix D. Generic Grain Input Simulating 19-perf Cylindrical Grains

Suggested input file for Generic Grain program simulation 19-perforation cylindrical grains.

```
c
c  19-perf cylindrical grain
c
c234567890123456789012345678901234567890123456789012345678901234567890
c   sliver 6
c typ nmbr   width     depth    perf      depth      perf     length
  2   12.  .091059   .164505    .06604   .189755    .0        1.70688
c   sliver 7
c typ nmbr   width     depth    perf      depth      perf     length
  2   12.  .091059   .189755    .0       .197896    .06604    1.70688
c typ nmbr  i-diam   o-diam    radians   length
  3   12.   .06604   .149098    0.5236   1.70688
c typ nmbr  perf      web      length
  4   24.   .06604   .116078   1.70688
c dat delta mult
  5  .001  10057.
```

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Appendix E. Generic Grain Output From 19-perf Cylindrical Grain Calculation

The output file from Generic Grain program using 19-perforation cylindrical grain input from appendix D.

```
 2  1.2000E+01  9.1059E-02  1.6451E-01  6.6040E-02  1.8975E-01  0.0000E+00  1.7069E+00

 2  1.2000E+01  9.1059E-02  1.8975E-01  0.0000E+00  1.9790E-01  6.6040E-02  1.7069E+00

 3  1.2000E+01  6.6040E-02  2.9820E-01  5.2360E-01  1.7069E+00  0.0000E+00  0.0000E+00

 4  2.4000E+01  6.6040E-02  1.1608E-01  1.7069E+00  0.0000E+00  0.0000E+00  0.0000E+00

 5  1.0000E-03  1.0057E+04  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
```

```
z brned     DEPTH BRNED       VOL       SURF          sfe          sfp          sfl

0.00000E+00  0.00000E+00  0.12957E+05  0.13723E+06  0.15096E+01  0.67284E+01  0.54071E+01
0.10536E-01  0.10000E-02  0.12820E+05  0.13888E+06  0.14954E+01  0.69241E+01  0.53900E+01
0.21200E-01  0.20000E-02  0.12682E+05  0.14053E+06  0.14810E+01  0.71192E+01  0.53730E+01
0.31991E-01  0.30000E-02  0.12542E+05  0.14217E+06  0.14664E+01  0.73139E+01  0.53560E+01
0.42909E-01  0.40000E-02  0.12401E+05  0.14380E+06  0.14516E+01  0.75081E+01  0.53390E+01
0.53952E-01  0.50000E-02  0.12258E+05  0.14543E+06  0.14365E+01  0.77019E+01  0.53221E+01
0.65121E-01  0.60000E-02  0.12113E+05  0.14705E+06  0.14213E+01  0.78951E+01  0.53052E+01
0.76415E-01  0.70000E-02  0.11967E+05  0.14866E+06  0.14057E+01  0.80879E+01  0.52883E+01
0.87833E-01  0.80000E-02  0.11819E+05  0.15027E+06  0.13900E+01  0.82802E+01  0.52714E+01
0.99375E-01  0.90000E-02  0.11669E+05  0.15187E+06  0.13740E+01  0.84720E+01  0.52546E+01
0.11104E+00  0.10000E-01  0.11518E+05  0.15346E+06  0.13579E+01  0.86634E+01  0.52377E+01
0.12283E+00  0.11000E-01  0.11365E+05  0.15505E+06  0.13414E+01  0.88543E+01  0.52209E+01
0.13474E+00  0.12000E-01  0.11211E+05  0.15662E+06  0.13248E+01  0.90447E+01  0.52042E+01
0.14677E+00  0.13000E-01  0.11055E+05  0.15820E+06  0.13079E+01  0.92346E+01  0.51874E+01
0.15892E+00  0.14000E-01  0.10898E+05  0.15976E+06  0.12908E+01  0.94240E+01  0.51707E+01
0.17120E+00  0.15000E-01  0.10739E+05  0.16132E+06  0.12735E+01  0.96130E+01  0.51540E+01
0.18359E+00  0.16000E-01  0.10578E+05  0.16287E+06  0.12560E+01  0.98015E+01  0.51373E+01
0.19610E+00  0.17000E-01  0.10416E+05  0.16442E+06  0.12382E+01  0.99895E+01  0.51207E+01
0.20874E+00  0.18000E-01  0.10252E+05  0.16595E+06  0.12202E+01  0.10177E+02  0.51041E+01
0.22149E+00  0.19000E-01  0.10087E+05  0.16748E+06  0.12020E+01  0.10364E+02  0.50875E+01
0.23436E+00  0.20000E-01  0.99202E+04  0.16901E+06  0.11835E+01  0.10551E+02  0.50709E+01
0.24734E+00  0.21000E-01  0.97519E+04  0.17053E+06  0.11648E+01  0.10737E+02  0.50544E+01
0.26045E+00  0.22000E-01  0.95822E+04  0.17204E+06  0.11459E+01  0.10922E+02  0.50378E+01
0.27367E+00  0.23000E-01  0.94109E+04  0.17354E+06  0.11268E+01  0.11107E+02  0.50213E+01
0.28700E+00  0.24000E-01  0.92381E+04  0.17504E+06  0.11075E+01  0.11292E+02  0.50049E+01
0.30046E+00  0.25000E-01  0.90638E+04  0.17653E+06  0.10879E+01  0.11476E+02  0.49884E+01
0.31402E+00  0.26000E-01  0.88880E+04  0.17801E+06  0.10681E+01  0.11660E+02  0.49720E+01
0.32770E+00  0.27000E-01  0.87108E+04  0.17949E+06  0.10480E+01  0.11843E+02  0.49556E+01
0.34150E+00  0.28000E-01  0.85320E+04  0.18096E+06  0.10278E+01  0.12026E+02  0.49392E+01
0.35541E+00  0.29000E-01  0.83518E+04  0.18242E+06  0.10073E+01  0.12208E+02  0.49229E+01
0.36943E+00  0.30000E-01  0.81702E+04  0.18387E+06  0.98657E+00  0.12390E+02  0.49066E+01
0.38356E+00  0.31000E-01  0.79870E+04  0.18532E+06  0.96564E+00  0.12571E+02  0.48903E+01
0.39780E+00  0.32000E-01  0.78025E+04  0.18677E+06  0.94447E+00  0.12752E+02  0.48740E+01
0.41216E+00  0.33000E-01  0.76165E+04  0.18820E+06  0.92308E+00  0.12933E+02  0.48578E+01
0.42663E+00  0.34000E-01  0.74290E+04  0.18963E+06  0.90146E+00  0.13112E+02  0.48416E+01
0.44120E+00  0.35000E-01  0.72402E+04  0.19105E+06  0.87962E+00  0.13292E+02  0.48254E+01
0.45589E+00  0.36000E-01  0.70499E+04  0.19247E+06  0.85755E+00  0.13471E+02  0.48092E+01
0.47068E+00  0.37000E-01  0.68582E+04  0.19387E+06  0.83525E+00  0.13649E+02  0.47931E+01
0.48559E+00  0.38000E-01  0.66651E+04  0.19528E+06  0.81273E+00  0.13827E+02  0.47769E+01
0.50060E+00  0.39000E-01  0.64706E+04  0.19667E+06  0.78998E+00  0.14005E+02  0.47608E+01
0.51572E+00  0.40000E-01  0.62747E+04  0.19806E+06  0.76700E+00  0.14182E+02  0.47448E+01
0.53094E+00  0.41000E-01  0.60774E+04  0.19944E+06  0.74380E+00  0.14358E+02  0.47287E+01
0.54628E+00  0.42000E-01  0.58787E+04  0.20081E+06  0.72038E+00  0.14534E+02  0.47127E+01
0.56172E+00  0.43000E-01  0.56787E+04  0.20218E+06  0.69672E+00  0.14710E+02  0.46967E+01
```

0.57726E+00	0.44000E-01	0.54773E+04	0.20354E+06	0.67284E+00	0.14885E+02	0.46808E+01
0.59291E+00	0.45000E-01	0.52746E+04	0.20489E+06	0.64874E+00	0.15060E+02	0.46648E+01
0.60866E+00	0.46000E-01	0.50704E+04	0.20624E+06	0.62441E+00	0.15234E+02	0.46489E+01
0.62452E+00	0.47000E-01	0.48650E+04	0.20758E+06	0.59985E+00	0.15408E+02	0.46330E+01
0.64048E+00	0.48000E-01	0.46582E+04	0.20891E+06	0.57506E+00	0.15581E+02	0.46171E+01
0.65654E+00	0.49000E-01	0.44501E+04	0.21024E+06	0.55005E+00	0.15753E+02	0.46013E+01
0.67271E+00	0.50000E-01	0.42406E+04	0.21156E+06	0.52482E+00	0.15926E+02	0.45855E+01
0.68898E+00	0.51000E-01	0.40298E+04	0.21287E+06	0.49935E+00	0.16098E+02	0.45697E+01
0.70534E+00	0.52000E-01	0.38178E+04	0.21418E+06	0.47366E+00	0.16269E+02	0.45539E+01
0.72181E+00	0.53000E-01	0.36044E+04	0.21548E+06	0.44775E+00	0.16440E+02	0.45382E+01
0.73838E+00	0.54000E-01	0.33897E+04	0.21677E+06	0.42161E+00	0.16610E+02	0.45225E+01
0.75505E+00	0.55000E-01	0.31737E+04	0.21805E+06	0.39524E+00	0.16780E+02	0.45068E+01
0.77182E+00	0.56000E-01	0.29565E+04	0.21933E+06	0.36864E+00	0.16949E+02	0.44911E+01
0.78868E+00	0.57000E-01	0.27379E+04	0.22060E+06	0.34182E+00	0.17118E+02	0.44755E+01
0.80565E+00	0.58000E-01	0.25181E+04	0.22187E+06	0.31478E+00	0.17287E+02	0.44599E+01
0.81959E+00	0.59000E-01	0.23375E+04	0.16916E+06	0.29256E+00	0.12983E+02	0.35448E+01
0.83196E+00	0.60000E-01	0.21773E+04	0.15494E+06	0.27286E+00	0.11593E+02	0.35403E+01
0.84338E+00	0.61000E-01	0.20293E+04	0.14426E+06	0.25463E+00	0.10553E+02	0.35359E+01
0.85405E+00	0.62000E-01	0.18911E+04	0.13535E+06	0.23759E+00	0.96889E+01	0.35314E+01
0.86408E+00	0.63000E-01	0.17611E+04	0.12755E+06	0.22154E+00	0.89344E+01	0.35270E+01
0.87354E+00	0.64000E-01	0.16386E+04	0.12054E+06	0.20638E+00	0.82566E+01	0.35225E+01
0.88248E+00	0.65000E-01	0.15227E+04	0.11411E+06	0.19203E+00	0.76359E+01	0.35180E+01
0.89094E+00	0.66000E-01	0.14130E+04	0.10813E+06	0.17843E+00	0.70597E+01	0.35136E+01
0.89896E+00	0.67000E-01	0.13092E+04	0.10241E+06	0.16552E+00	0.65141E+01	0.35036E+01
0.90645E+00	0.68000E-01	0.12120E+04	0.94673E+05	0.15344E+00	0.58845E+01	0.33757E+01
0.91338E+00	0.69000E-01	0.11223E+04	0.87570E+05	0.14225E+00	0.52980E+01	0.32672E+01
0.91979E+00	0.70000E-01	0.10393E+04	0.80928E+05	0.13190E+00	0.47441E+01	0.31709E+01
0.92570E+00	0.71000E-01	0.96264E+03	0.74645E+05	0.12233E+00	0.42166E+01	0.30833E+01
0.93115E+00	0.72000E-01	0.89210E+03	0.68658E+05	0.11351E+00	0.37111E+01	0.30023E+01
0.93626E+00	0.73000E-01	0.82588E+03	0.66299E+05	0.10522E+00	0.35606E+01	0.29264E+01
0.94123E+00	0.74000E-01	0.76146E+03	0.64534E+05	0.97139E-01	0.34648E+01	0.28549E+01
0.94607E+00	0.75000E-01	0.69870E+03	0.62852E+05	0.89248E-01	0.33735E+01	0.27869E+01
0.95079E+00	0.76000E-01	0.63755E+03	0.61244E+05	0.81542E-01	0.32861E+01	0.27220E+01
0.95540E+00	0.77000E-01	0.57793E+03	0.59698E+05	0.74011E-01	0.32022E+01	0.26597E+01
0.95988E+00	0.78000E-01	0.51978E+03	0.58207E+05	0.66651E-01	0.31213E+01	0.25998E+01
0.96426E+00	0.79000E-01	0.46306E+03	0.56767E+05	0.59454E-01	0.30431E+01	0.25419E+01
0.96853E+00	0.80000E-01	0.40771E+03	0.55370E+05	0.52416E-01	0.29673E+01	0.24860E+01
0.97270E+00	0.81000E-01	0.35371E+03	0.54015E+05	0.45531E-01	0.28937E+01	0.24317E+01
0.97677E+00	0.82000E-01	0.30100E+03	0.52696E+05	0.38797E-01	0.28220E+01	0.23789E+01
0.98037E+00	0.83000E-01	0.25431E+03	0.41251E+05	0.32821E-01	0.22454E+01	0.18235E+01
0.98331E+00	0.84000E-01	0.21629E+03	0.36140E+05	0.27951E-01	0.19812E+01	0.15844E+01
0.98590E+00	0.85000E-01	0.18268E+03	0.32158E+05	0.23638E-01	0.17723E+01	0.14016E+01
0.98821E+00	0.86000E-01	0.15272E+03	0.28691E+05	0.19788E-01	0.15884E+01	0.12446E+01
0.99027E+00	0.87000E-01	0.12603E+03	0.25543E+05	0.16350E-01	0.14199E+01	0.11035E+01
0.99210E+00	0.88000E-01	0.10232E+03	0.22620E+05	0.13292E-01	0.12622E+01	0.97366E+00
0.99372E+00	0.89000E-01	0.81407E+02	0.19868E+05	0.10589E-01	0.11126E+01	0.85241E+00
0.99513E+00	0.90000E-01	0.63141E+02	0.17254E+05	0.82237E-02	0.96936E+00	0.73802E+00
0.99634E+00	0.91000E-01	0.47394E+02	0.14753E+05	0.61809E-02	0.83148E+00	0.62931E+00
0.99737E+00	0.92000E-01	0.34065E+02	0.12349E+05	0.44484E-02	0.69807E+00	0.52543E+00
0.99822E+00	0.93000E-01	0.23063E+02	0.10029E+05	0.30157E-02	0.56850E+00	0.42573E+00
0.99890E+00	0.94000E-01	0.14311E+02	0.77828E+04	0.18737E-02	0.44230E+00	0.32970E+00
0.99940E+00	0.95000E-01	0.77396E+01	0.56020E+04	0.10147E-02	0.31906E+00	0.23695E+00
0.99975E+00	0.96000E-01	0.32878E+01	0.34804E+04	0.43161E-03	0.19848E+00	0.14715E+00
0.99993E+00	0.97000E-01	0.89977E+00	0.14126E+04	0.11827E-03	0.80303E-01	0.60033E-01
0.99999E+00	0.98000E-01	0.91446E-01	0.39853E+03	0.12036E-04	0.22643E-01	0.16972E-01
0.10000E+01	0.99000E-01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00

Appendix F. IBHVG2 Calculations Using 19-perf Cylindrical Propellant

IBHVG2 output with 19-perforation cylindrical propellant grains.

```
  ERRTOL=  1.1920929E-07
1                                                          IBHVG2.506     DATE             TIME

0 CARD   1 --> $COMM
  CARD   2 -->          FROM IBHVG2 BENCHMARK TEST CASE 1
  CARD   3 --> $INFO
  CARD   4 -->         POPT=1,2,1,0   $  ECHO INPUT LINES, PRINT TRAJECTORY + SUMMARY
  CARD   5 -->         RUN='M30 19-PERF - LOT UNKNOWN'
  CARD   6 -->         GRAD = 3       $ INVOKE CHAMBRAGE GRADIENT
  CARD   7 --> $TDIS
  CARD   8 -->         SHOW='TIME' REMK='TIME'
  CARD   9 --> $TDIS
  CARD  10 -->         SHOW='TRAV' REMK='TRAV'
  CARD  11 --> $TDIS
  CARD  12 -->         SHOW='Z(2)' REMK='FRAC BRND'
  CARD  13 --> $TDIS
  CARD  14 -->         SHOW='DB-P(2)' REMK='DB BRND CM' MULT=100.
  CARD  15 --> $TDIS
  CARD  16 -->         SHOW='SRF(2)' REMK='SRF (CM2)' MULT=10000.
  CARD  17 --> $GUN
  CARD  18 -->         NAME='HARP GUN'   $ SMOOTHBORE
  CARD  19 -->         CHAM=0.072   GRVE=.1852168   LAND=.1852168
  CARD  20 -->         TRAV=5.0  TWST=99
  CARD  21 -->         CPTS = 3  DIST = 0.0,    1.3900,   1.5000
  CARD  22 -->                   DIAM = 0.250,  0.250,     0.1852168
  CARD  23 --> $COMMENT
  CARD  24 -->         PRIMER IS ASSUMED ALL BURNED AT TIME=0.0
  CARD  25 -->         IGNITER CHARGE IS PROPELLANT 1
  CARD  26 -->         MAIN CHARGE IS PROPELLANT 2
  CARD  27 --> $PRIM
  CARD  28 -->         NAME='BLK POWDER'  CHWT=.006985322
  CARD  29 -->         GAMA=1.25   TEMP=2000   FORC=286950.  $ FORC=J/KG
  CARD  30 -->         COV=.001083818                        $ COV=M3/KG
  CARD  31 --> $PROP
  CARD  32 -->         NAME='BLK POWDER'  GRAN='CORD' CHWT=.6803885
  CARD  33 -->         LEN=.0050292 DIAM=.0024892 RHO=1660.794  TEMP=2000
  CARD  34 -->         GAMA=1.25    FORC=286950.  COV=.001264455
  CARD  35 -->         ALPH=0.0     BETA=0.508
  CARD  36 -->            $ BETA(M/S)=BETA(PSI)*0.0254 WHEN ALPH=0.0
  CARD  37 --> $PROP
  CARD  38 -->         NAME='M30 LOT UNKNOWN'     GRAN='19P'  CHWT=22.
  CARD  39 -->         TEMP=3012    RHO=1680.17                   $ DENSITY=KG/M3
  CARD  40 -->         LEN=.01706880 PD=.0006604    WEB=.00116078  $ LENGTH=METERS
  CARD  41 -->         GAMA=1.2441  FORC=1075693. COV=.001027496   $ FORC=J/KG COV=M3/KG
  CARD  42 -->         NTBL=4   PR4L=41.368542,68.94757,82.737084,275.79028    $ PRES=MPA
  CARD  43 -->                  BR4L=.0508,.065024,.06985,.1508760 $ RATE=M/S
  CARD  44 --> $PROJ
  CARD  45 -->         NAME='PLASTIC LAB SABOT' PRWT=23.58576
  CARD  46 --> $RESI
  CARD  47 -->         NPTS=4
  CARD  48 -->         TRAV=0,    .00762,   .07620,   15.24              $ DIST=METERS
  CARD  49 -->         PRES=.6894757, 27.579028,   12.4105626,   5.5158   $ PRES=MPA
  CARD  50 --> $END
1M30 19-PERF - LOT UNKNOWN                         IBHVG2.506     DATE             TIME

0  CHAMBER DESCRIPTION      INTEGRATED VOLUME    0.0723527

       POSITION     DIAMETER
         (M)          (M)
 1     0.0000000    0.2500000
```

```
 2     1.3900000    0.2500000
 3     1.5000000    0.1852168
 **WARNING** CHAMBER VOLUME OVERRIDDEN BY COMPUTED VALUE
1M30 19-PERF - LOT UNKNOWN                         IBHVG2.506     DATE            TIME


 ------------
 - GUN TUBE -
 ------------

TYPE: HARP GUN                  CHAMBER VOLUME (M3):  0.07235   TRAVEL (M):          5.00000
GROOVE DIAMETER (M):  0.18522  LAND DIAMETER (M):    0.18522   GROOVE/LAND RATIO (-): 0.000
TWIST (CALS/TURN):       99.0  BORE AREA (M2):       0.02694   HEAT-LOSS OPTION:      1
 **WARNING: GROOVE/LAND RATIO .LE. 0., GUN TUBE IS ASSUMED TO BE SMOOTH-BORE OF DIAMETER 0.18522
SHELL THICKNESS (M):    0.000102   SHELL CP (J/KG-K):    60.3163
SHELL DENSITY (KG/M3): 7861.0918
INITIAL SHELL TEMP (K):     293.   AIR H0 (W/M**2-K):    11.3482

 --------------
 - PROJECTILE -
 --------------

TYPE: PLASTIC LAB SABOT      TOTAL WEIGHT (KG):   23.586   WEIGHT PREDICTOR OPTION:    0

 --------------
 - RESISTANCE -
 --------------

AIR RESISTANCE OPTION:           1      TUBE GAS INITIAL PRES (MPA)  0.000
WALL HEATING FRACTION:       0.000
RESISTIVE PRESSURE MULT INDEX:   3      RESISTIVE FACTOR            1.000
FRICTION TABLE LENGTH:           4

 I  TRAVEL (M) PRESSURE (MPA)  I  TRAVEL (M) PRESSURE (MPA)  I  TRAVEL (M) PRESSURE (MPA)

 1   0.000        0.689        3   0.076       12.411        4  15.240        5.516
 2   0.008       27.579

 -----------
 - GENERAL -
 -----------

MAX TIME STEP (S):         0.000100       PRINT STEP (S):           0.000000       MAX RELATIVE
ERROR (-):     0.00200
PRINT OPTIONS:          1 2 1 0 1 1       STORE OPTION:                      0       CONSTANT-
PRESSURE OPTION:         0
GRADIENT MODEL: CHAMBRAGE

 ----------
 - RECOIL -
 ----------

RECOIL OPTION:                   0       TYPE:                                       RECOILING
WEIGHT (KG):           0.

 ----------
 - PRIMER -
 ----------

TYPE: BLK POWDER                GAMMA (-):         1.2500       FORCE (J/KG):      286950.
COVOLUME (M3/KG):   1.0838E-03  FLAME TEMP (K):    2000.0       WEIGHT (KG):      0.006985
1M30 19-PERF - LOT UNKNOWN                         IBHVG2.506     DATE            TIME


 ------------
 - CHARGE 1 -
 ------------

TYPE: BLK POWDER        GRAINS:   16739.     CORD     WEIGHT (KG):   0.6804
EROSIVE COEFF (-):   0.000000     CHARGE IGN CODE:   0   CHARGE IGN AT (S): 0.00000E+00
GRAIN LENGTH (M):    0.005029     GRAIN DIAMETER (M):   0.002489
```

```
PROPERTIES AT LAYER BOUNDARIES OF END SURFACES     PROPERTIES AT LAYER BOUNDARIES OF LAT SURFACES
                        1ST     2ND     3RD     4TH         1ST     2ND     3RD     4TH
AT DEPTH (M):          ------ ------  ------  0.00000     ------  ------  ------  0.00000
ADJACENT LAYER WT %:   ------ ------  ------  100.000     ------  ------  ------  100.000
DENSITY (KG/M3):       ------ ------  ------ 1660.794     ------  ------  ------ 1660.794
GAMMA (-):             ------ ------  ------   1.2500     ------  ------  ------   1.2500
FORCE (J/KG):          ------ ------  ------  286950.     ------  ------  ------  286950.
COVOLUME (M3/KG):      ------ ------  ------ 1.2645E-03   ------  ------  ------ 1.2645E-03
FLAME TEMP (K):        ------ ------  ------   2000.0     ------  ------  ------   2000.0
BURNING RATE EXPS:     ------ ------  ------   0.0000     ------  ------  ------   0.0000
BURNING RATE COEFFS:   ------ ------  ------   0.5080     ------  ------  ------   0.5080


 ------------
 - CHARGE 2 -
 ------------

TYPE: M30 LOT UNKNOWN          GRAINS:          10057.   19P  WEIGHT (KG):     22.0000
EROSIVE COEFF (-): 0.000000   CHARGE IGN CODE:      0       CHARGE IGN AT (S):  0.00000E+00
GRAIN LENGTH (M):  0.017069   GRAIN DIAMETER (M): 0.010267  PERF DIAMETER (M):  0.000660
INNER WEB (M):     0.001161   MIDDLE WEB (M):     0.001161  OUTER WEB (M):      0.001161

PROPERTIES AT LAYER BOUNDARIES OF PERF SURFACES  PROPERTIES AT LAYER BOUNDARIES OF END SURFACES
                        1ST     2ND     3RD     4TH         1ST     2ND     3RD     4TH
AT DEPTH (M):         ------  ------  ------  0.00000     ------  ------  ------  0.00000
ADJACENT LAYER WT %:  ------  ------  ------  100.000     ------  ------  ------  100.000
DENSITY (KG/M3):      ------  ------  ------ 1680.170     ------  ------  ------ 1680.170
GAMMA (-):            ------  ------  ------   1.2441     ------  ------  ------   1.2441
FORCE (J/KG):         ------  ------  ------ 1075693.     ------  ------  ------ 1075693.
COVOLUME (M3/KG):     ------  ------  ------ 1.0275E-03   ------  ------  ------  1.0275E-03
FLAME TEMP (K):       ------  ------  ------   3012.0     ------  ------  ------   3012.0
MEAN PRESSURES (MPA): ------  ------  ------   41.369     ------  ------  ------   41.369
MEAN PRESSURES (MPA): ------  ------  ------   68.948     ------  ------  ------   68.948
MEAN PRESSURES (MPA): ------  ------  ------   82.737     ------  ------  ------   82.737
MEAN PRESSURES (MPA): ------  ------  ------  275.790     ------  ------  ------  275.790
BURNING RATES (M/S):  ------  ------  ------  0.05080     ------  ------  ------  0.05080
BURNING RATES (M/S):  ------  ------  ------  0.06502     ------  ------  ------  0.06502
BURNING RATES (M/S):  ------  ------  ------  0.06985     ------  ------  ------  0.06985
BURNING RATES (M/S):  ------  ------  ------  0.15088     ------  ------  ------  0.15088

                         PROPERTIES AT LAYER BOUNDARIES OF  LAT SURFACES
                               1ST         2ND         3RD         4TH

   AT DEPTH (M):              ------      ------      ------     0.00000
   ADJACENT LAYER WT %:       ------      ------      ------     100.000
   DENSITY (KG/M3):           ------      ------      ------    1680.170
   GAMMA (-):                 ------      ------      ------      1.2441
   FORCE (J/KG):              ------      ------      ------    1075693.
   COVOLUME (M3/KG):          ------      ------      ------  1.0275E-03
   FLAME TEMP (K):            ------      ------      ------      3012.0
   MEAN PRESSURES (MPA):      ------      ------      ------      41.369
   MEAN PRESSURES (MPA):      ------      ------      ------      68.948
   MEAN PRESSURES (MPA):      ------      ------      ------      82.737
   MEAN PRESSURES (MPA):      ------      ------      ------     275.790
   BURNING RATES (M/S):       ------      ------      ------     0.05080
   BURNING RATES (M/S):       ------      ------      ------     0.06502
   BURNING RATES (M/S):       ------      ------      ------     0.06985
   BURNING RATES (M/S):       ------      ------      ------     0.15088
1M30 19-PERF - LOT UNKNOWN                         IBHVG2.506     DATE             TIME

      TRAJECTORY VARIABLES: / 1/  TRAJ 1  TIME          TIME
                            / 2/  TRAJ 1  TRAV          TRAV
                            / 3/  TRAJ 1  Z(2)          FRAC BRND
                            / 4/  TRAJ 1  DB-P(2)       DB BRND CM
                            / 5/  TRAJ 1  SRF(2)        SRF (CM2)

    / 1/        / 2/        / 3/        / 4/        / 5/
0 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.13838E+06
  0.10000E+00 0.00000E+00 0.45641E-03 0.43176E-04 0.13845E+06
  0.12395     0.00000E+00 0.62493E-03 0.59112E-04 0.13848E+06
```

```
 SHOT-START PRESSURE ACHIEVED
  0.20000     0.47785E-06 0.12769E-02 0.12074E-03 0.13858E+06
  0.30000     0.61196E-05 0.23722E-02 0.22416E-03 0.13875E+06
  0.40000     0.24195E-04 0.37074E-02 0.35007E-03 0.13896E+06
  0.50000     0.62343E-04 0.52623E-02 0.49647E-03 0.13920E+06
  0.60000     0.12820E-03 0.70239E-02 0.66201E-03 0.13947E+06
  0.70000     0.22909E-03 0.89829E-02 0.84572E-03 0.13977E+06
  0.80000     0.37169E-03 0.11132E-01 0.10468E-02 0.14011E+06
  0.90000     0.56182E-03 0.13467E-01 0.12648E-02 0.14046E+06
  1.00000     0.80416E-03 0.15984E-01 0.14990E-02 0.14085E+06
   1.1000     0.11021E-02 0.18679E-01 0.17492E-02 0.14126E+06
   1.2000     0.14577E-02 0.21551E-01 0.20150E-02 0.14170E+06
   1.3000     0.18713E-02 0.24598E-01 0.22962E-02 0.14216E+06
   1.4000     0.23420E-02 0.27820E-01 0.25924E-02 0.14264E+06
   1.5000     0.28672E-02 0.31215E-01 0.29035E-02 0.14315E+06
   1.6000     0.34432E-02 0.34784E-01 0.32294E-02 0.14368E+06
   1.7000     0.40647E-02 0.38528E-01 0.35699E-02 0.14424E+06
   1.8000     0.47258E-02 0.42446E-01 0.39248E-02 0.14482E+06
   1.9000     0.54193E-02 0.46539E-01 0.42942E-02 0.14542E+06
   2.0000     0.61380E-02 0.50810E-01 0.46779E-02 0.14604E+06
   2.1000     0.68741E-02 0.55258E-01 0.50759E-02 0.14668E+06
   2.2000     0.76199E-02 0.59886E-01 0.54881E-02 0.14735E+06
   2.3000     0.83728E-02 0.64696E-01 0.59145E-02 0.14804E+06
   2.4000     0.91503E-02 0.69690E-01 0.63551E-02 0.14875E+06
   2.4500     0.95554E-02 0.72256E-01 0.65808E-02 0.14911E+06
 PROPELLANT 1 BURNED OUT
   2.5000     0.99752E-02 0.74869E-01 0.68100E-02 0.14948E+06
   2.6000     0.10871E-01 0.80237E-01 0.72790E-02 0.15023E+06
   2.7000     0.11863E-01 0.85797E-01 0.77623E-02 0.15101E+06
   2.8000     0.12976E-01 0.91551E-01 0.82600E-02 0.15180E+06
   2.9000     0.14238E-01 0.97503E-01 0.87720E-02 0.15262E+06
   3.0000     0.15676E-01 0.10365     0.92983E-02 0.15346E+06
   3.1000     0.17318E-01 0.11001     0.98391E-02 0.15431E+06
   3.2000     0.19197E-01 0.11657     0.10394E-01 0.15519E+06
   3.3000     0.21342E-01 0.12335     0.10964E-01 0.15609E+06
   3.4000     0.23787E-01 0.13033     0.11548E-01 0.15702E+06
   3.5000     0.26567E-01 0.13753     0.12147E-01 0.15796E+06
   3.6000     0.29716E-01 0.14495     0.12760E-01 0.15892E+06
   3.7000     0.33273E-01 0.15260     0.13388E-01 0.15990E+06
   3.8000     0.37277E-01 0.16047     0.14031E-01 0.16090E+06
   3.9000     0.41766E-01 0.16855     0.14686E-01 0.16192E+06
   4.0000     0.46785E-01 0.17682     0.15353E-01 0.16296E+06
   4.1000     0.52375E-01 0.18530     0.16032E-01 0.16401E+06
   4.2000     0.58582E-01 0.19397     0.16722E-01 0.16507E+06
   4.3000     0.65452E-01 0.20286     0.17425E-01 0.16615E+06
   4.4000     0.73034E-01 0.21204     0.18147E-01 0.16725E+06
   4.5000     0.81376E-01 0.22152     0.18886E-01 0.16838E+06
1M30 19-PERF - LOT UNKNOWN                         IBHVG2.506     DATE              TIME

      TRAJECTORY VARIABLES: / 1/  TRAJ 1  TIME          TIME
                            / 2/  TRAJ 1  TRAV          TRAV
                            / 3/  TRAJ 1  Z(2)          FRAC BRND
                            / 4/  TRAJ 1  DB-P(2)       DB BRND CM
                            / 5/  TRAJ 1  SRF(2)        SRF (CM2)

    / 1/        / 2/        / 3/        / 4/        / 5/
0  4.6000     0.90521E-01 0.23130     0.19644E-01 0.16954E+06
   4.7000     0.10050     0.24139     0.20421E-01 0.17071E+06
   4.8000     0.11135     0.25179     0.21215E-01 0.17192E+06
   4.9000     0.12310     0.26251     0.22029E-01 0.17314E+06
   5.0000     0.13579     0.27355     0.22861E-01 0.17439E+06
   5.1000     0.14944     0.28491     0.23711E-01 0.17566E+06
   5.2000     0.16411     0.29661     0.24579E-01 0.17695E+06
   5.3000     0.17981     0.30863     0.25466E-01 0.17827E+06
   5.4000     0.19658     0.32100     0.26371E-01 0.17960E+06
   5.5000     0.21445     0.33370     0.27293E-01 0.18096E+06
   5.6000     0.23347     0.34674     0.28233E-01 0.18233E+06
   5.7000     0.25365     0.36013     0.29191E-01 0.18373E+06
   5.8000     0.27503     0.37386     0.30166E-01 0.18514E+06
   5.9000     0.29764     0.38794     0.31158E-01 0.18657E+06
   6.0000     0.32152     0.40236     0.32166E-01 0.18802E+06
```

```
   6.1000     0.34669     0.41714     0.33191E-01 0.18949E+06
   6.2000     0.37318     0.43226     0.34232E-01 0.19097E+06
   6.3000     0.40103     0.44773     0.35288E-01 0.19247E+06
   6.4000     0.43025     0.46354     0.36360E-01 0.19398E+06
   6.5000     0.46087     0.47970     0.37446E-01 0.19550E+06
   6.6000     0.49293     0.49620     0.38547E-01 0.19703E+06
   6.7000     0.52644     0.51304     0.39662E-01 0.19858E+06
   6.8000     0.56144     0.53022     0.40790E-01 0.20013E+06
   6.9000     0.59793     0.54773     0.41931E-01 0.20170E+06
   7.0000     0.63595     0.56557     0.43085E-01 0.20327E+06
   7.1000     0.67552     0.58374     0.44251E-01 0.20485E+06
   7.2000     0.71666     0.60223     0.45428E-01 0.20644E+06
   7.3000     0.75938     0.62104     0.46617E-01 0.20803E+06
   7.4000     0.80371     0.64016     0.47815E-01 0.20962E+06
   7.5000     0.84966     0.65958     0.49024E-01 0.21122E+06
   7.6000     0.89726     0.67931     0.50242E-01 0.21282E+06
   7.7000     0.94650     0.69933     0.51470E-01 0.21443E+06
   7.8000     0.99742     0.71964     0.52705E-01 0.21603E+06
   7.9000      1.0500     0.74023     0.53949E-01 0.21763E+06
   8.0000      1.1043     0.76109     0.55199E-01 0.21923E+06
   8.1000      1.1603     0.78223     0.56457E-01 0.22083E+06
   8.2000      1.2180     0.80362     0.57721E-01 0.22243E+06
   8.3000      1.2775     0.82294     0.58990E-01 0.18051E+06
   8.3260      1.2933     0.82741     0.59321E-01 0.17385E+06
 LOCAL PRESSURE MAX DETECTED
   8.4000      1.3387     0.83931     0.60260E-01 0.15880E+06
   8.5000      1.4016     0.85389     0.61527E-01 0.14307E+06
   8.6000      1.4662     0.86704     0.62790E-01 0.13014E+06
   8.7000      1.5325     0.87898     0.64046E-01 0.11892E+06
   8.8000      1.6005     0.88983     0.65294E-01 0.10890E+06
   8.9000      1.6702     0.89970     0.66533E-01  99771.
   9.0000      1.7415     0.90867     0.67762E-01  91345.
   9.1000      1.8144     0.91680     0.68980E-01  83493.
   9.2000      1.8888     0.92414     0.70186E-01  76123.
   9.3000      1.9648     0.93076     0.71380E-01  69166.
1M30 19-PERF - LOT UNKNOWN                        IBHVG2.506     DATE              TIME

      TRAJECTORY VARIABLES: / 1/  TRAJ 1  TIME          TIME
                            / 2/  TRAJ 1  TRAV          TRAV
                            / 3/  TRAJ 1  Z(2)          FRAC BRND
                            / 4/  TRAJ 1  DB-P(2)       DB BRND CM
                            / 5/  TRAJ 1  SRF(2)        SRF (CM2)

    / 1/        / 2/        / 3/        / 4/        / 5/
0  9.4000      2.0424     0.93672     0.72560E-01  64258.
   9.5000      2.1214     0.94236     0.73726E-01  62408.
   9.6000      2.2019     0.94778     0.74879E-01  60646.
   9.7000      2.2838     0.95298     0.76019E-01  58961.
   9.8000      2.3671     0.95798     0.77144E-01  57346.
   9.9000      2.4518     0.96279     0.78256E-01  55796.
  10.0000      2.5378     0.96740     0.79355E-01  54304.
   10.100      2.6252     0.97184     0.80440E-01  52866.
   10.200      2.7138     0.97611     0.81511E-01  51478.
   10.300      2.8036     0.98017     0.82569E-01  46751.
   10.400      2.8948     0.98354     0.83614E-01  38696.
   10.500      2.9871     0.98638     0.84645E-01  33680.
   10.600      3.0805     0.98884     0.85663E-01  29554.
   10.700      3.1752     0.99096     0.86666E-01  25927.
   10.800      3.2709     0.99279     0.87656E-01  22637.
   10.900      3.3678     0.99437     0.88632E-01  19600.
   11.000      3.4657     0.99570     0.89594E-01  16764.
   11.100      3.5647     0.99682     0.90543E-01  14093.
   11.200      3.6646     0.99774     0.91479E-01  11562.
   11.300      3.7656     0.99846     0.92402E-01  9154.6
   11.400      3.8676     0.99902     0.93311E-01  6854.7
   11.500      3.9705     0.99941     0.94208E-01  4651.4
   11.600      4.0743     0.99966     0.95092E-01  2535.3
   11.700      4.1790     0.99976     0.95964E-01  498.80
   11.725      4.2054      1.0000     0.96180E-01 0.00000E+00
 PROPELLANT 2 BURNED OUT
   11.800      4.2846      1.0000     0.96180E-01 0.00000E+00
```

11.900	4.3911	1.0000	0.96180E-01	0.00000E+00
12.000	4.4984	1.0000	0.96180E-01	0.00000E+00
12.100	4.6065	1.0000	0.96180E-01	0.00000E+00
12.200	4.7154	1.0000	0.96180E-01	0.00000E+00
12.300	4.8251	1.0000	0.96180E-01	0.00000E+00
12.400	4.9356	1.0000	0.96180E-01	0.00000E+00
12.458	5.0000	1.0000	0.96180E-01	0.00000E+00

PROJECTILE EXIT

1M30 19-PERF - LOT UNKNOWN IBHVG2.506 DATE TIME

CONDITIONS AT:	PMAX	MUZZLE
TIME (MS):	8.326	12.458
TRAVEL (M):	1.2933	5.0000
VELOCITY (M/S)	607.69	1112.62
ACCELERATION (G):	17650.	7491.
BREECH PRESS (MPA):	226.5169	110.3095
MEAN PRESS (MPA):	210.6532	98.2994
BASE PRESS (MPA):	164.0010	76.3498
MEAN TEMP (K):	2725.	2269.
Z CHARGE 1 (-):	1.000	1.000
Z CHARGE 2 (-):	0.827	1.000

ENERGY BALANCE SUMMARY	JOULE	%
TOTAL CHEMICAL:	97714744.	100.00
(1) INTERNAL GAS:	73915056.	75.64
(2) WORK AND LOSSES:	23799686.	24.36
(A) PROJECTILE KINETIC:	14598617.	14.94
(B) GAS KINETIC:	4548974.	4.66
(C) PROJECTILE ROTATIONAL:	7350.	0.01
(D) FRICTIONAL WORK TO TUBE:	0.	0.00
(E) OTHER FRICTIONAL WORK:	1537768.	1.57
(F) WORK DONE AGAINST AIR:	144518.	0.15
(G) HEAT CONVECTED TO BORE:	2962459.	3.03
(H) RECOIL ENERGY:	0.	0.00

LOADING DENSITY (KG/M3):	313.566
CHARGE WT/PROJECTILE WT:	0.962
PIEZOMETRIC EFFICIENCY:	0.478
EXPANSION RATIO:	2.862

Appendix G. IBHVG2 Output Using Data From Generic Grain Program

IBHVG2 output using GEN grain input array from Generic Grain program.

```
  ERRTOL=  1.1920929E-07
1                                                   IBHVG2.506     DATE             TIME

0 CARD   1 --> $COMM
  CARD   2 -->          FROM IBHVG2 BENCHMARK TEST CASE 1
  CARD   3 --> $INFO
  CARD   4 -->         POPT=1,2,1,0   $  ECHO INPUT LINES, PRINT TRAJECTORY + SUMMARY
  CARD   5 -->         RUN='M30 GEN GRAIN'
  CARD   6 -->         GRAD = 3       $ INVOKE CHAMBRAGE GRADIENT
  CARD   7 --> $TDIS
  CARD   8 -->         SHOW='TIME' REMK='TIME'
  CARD   9 --> $TDIS
  CARD  10 -->         SHOW='TRAV' REMK='TRAV'
  CARD  11 --> $TDIS
  CARD  12 -->         SHOW='Z(2)' REMK='FRAC BRND'
  CARD  13 --> $TDIS
  CARD  14 -->         SHOW='DB-P(2)' REMK='DB BRND CM' MULT=100.
  CARD  15 --> $TDIS
  CARD  16 -->         SHOW='SRF(2)' REMK='SRF (CM2)' MULT=10000.
  CARD  17 --> $GUN
  CARD  18 -->         NAME='HARP GUN'   $ SMOOTHBORE
  CARD  19 -->         CHAM=0.072   GRVE=.1852168   LAND=.1852168
  CARD  20 -->         TRAV=5.0  TWST=99
  CARD  21 -->         CPTS = 3  DIST = 0.0,    1.3900,   1.5000
  CARD  22 -->                   DIAM = 0.250,  0.250,     0.1852168
  CARD  23 --> $COMMENT
  CARD  24 -->         PRIMER IS ASSUMED ALL BURNED AT TIME=0.0
  CARD  25 -->         IGNITER CHARGE IS PROPELLANT 1
  CARD  26 -->         MAIN CHARGE IS PROPELLANT 2
  CARD  27 --> $PRIM
  CARD  28 -->         NAME='BLK POWDER'  CHWT=.006985322
  CARD  29 -->         GAMA=1.25   TEMP=2000   FORC=286950.  $ FORC=J/KG
  CARD  30 -->         COV=.001083818                        $ COV=M3/KG
  CARD  31 --> $PROP
  CARD  32 -->         NAME='BLK POWDER'  GRAN='CORD' CHWT=.6803885
  CARD  33 -->         LEN=.0050292 DIAM=.0024892 RHO=1660.794  TEMP=2000
  CARD  34 -->         GAMA=1.25    FORC=286950.  COV=.001264455
  CARD  35 -->         ALPH=0.0     BETA=0.508
  CARD  36 -->            $ BETA(M/S)=BETA(PSI)*0.0254 WHEN ALPH=0.0
  CARD  37 --> $PROP
  CARD  38 -->         NAME='M30 LOT UNKNOWN'     GRAN='GEN'  CHWT=22.
  CARD  39 -->         TEMP=3012    RHO=1680.17                  $ DENSITY=KG/M3
  CARD  40 -->         LEN=.01706880 PD=.0006604    WEB=.00116078  $ LENGTH=METERS
  CARD  41 -->         GAMA=1.2441  FORC=1075693. COV=.001027496   $ FORC=J/KG COV=M3/KG
  CARD  42 -->         NTBL=4   PR4L=41.368542,68.94757,82.737084,275.79028    $ PRES=MP
  CARD  43 -->                  BR4L=.0508,.065024,.06985,.1508760 $ RATE=M/S
  CARD  44 -->         NSUR=20
  CARD  45 -->         DEPB=0., .00025, .00058, .00059, .00060, .00063, .00064, .00065,
  CARD  46 -->              .00067, .00069, .00071, .00072, .00073, .00075, .00082,
  CARD  47 -->              .00083, .00085, .00090, .00094, .00099
  CARD  48 -->         SURF=13.723, 17.653, 22.187, 16.916, 15.494, 12.755, 12.054,
  CARD  49 -->              11.411, 10.241, 8.7570, 7.4645, 6.8658, 6.6299, 6.2852,
  CARD  50 -->              5.2696, 4.1251, 3.2158, 1.7254, 0.77828, 0.0
  CARD  51 --> $PROJ
  CARD  52 -->         NAME='PLASTIC LAB SABOT' PRWT=23.58576
  CARD  53 --> $RESI
  CARD  54 -->         NPTS=4
  CARD  55 -->         TRAV=0,    .00762,   .07620,   15.24               $ DIST=METERS
1M30 GEN GRAIN                                      IBHVG2.506     DATE             TIME
```

```
0 CARD  56 -->         PRES=.6894757, 27.579028,   12.4105626,   5.5158   $ PRES=MPA
  CARD  57 --> $END
1M30 GEN GRAIN                                     IBHVG2.506     DATE            TIME
0  CHAMBER DESCRIPTION      INTEGRATED VOLUME    0.0723527

       POSITION     DIAMETER
         (M)          (M)
 1     0.0000000    0.2500000
 2     1.3900000    0.2500000
 3     1.5000000    0.1852168
 **WARNING** CHAMBER VOLUME OVERRIDDEN BY COMPUTED VALUE
1M30 GEN GRAIN                                     IBHVG2.506     DATE            TIME

 ------------
 - GUN TUBE -
 ------------

TYPE: HARP GUN                  CHAMBER VOLUME (M3):  0.07235   TRAVEL (M):          5.00000
GROOVE DIAMETER (M):  0.18522  LAND DIAMETER (M):    0.18522   GROOVE/LAND RATIO (-): 0.000
TWIST (CALS/TURN):       99.0  BORE AREA (M2):       0.02694   HEAT-LOSS OPTION:      1
 **WARNING: GROOVE/LAND RATIO .LE. 0., GUN TUBE IS ASSUMED TO BE SMOOTH-BORE OF DIAMETER 0.18522
SHELL THICKNESS (M):    0.000102   SHELL CP (J/KG-K):    60.3163
SHELL DENSITY (KG/M3): 7861.0918
INITIAL SHELL TEMP (K):     293.   AIR H0 (W/M**2-K):    11.3482

 --------------
 - PROJECTILE -
 --------------

TYPE: PLASTIC LAB SABOT      TOTAL WEIGHT (KG):   23.586   WEIGHT PREDICTOR OPTION:    0

 --------------
 - RESISTANCE -
 --------------

AIR RESISTANCE OPTION:           1      TUBE GAS INITIAL PRES (MPA)  0.000
WALL HEATING FRACTION:        0.000
RESISTIVE PRESSURE MULT INDEX:    3      RESISTIVE FACTOR            1.000
FRICTION TABLE LENGTH:           4

 I  TRAVEL (M) PRESSURE (MPA)  I  TRAVEL (M) PRESSURE (MPA)  I  TRAVEL (M) PRESSURE (MPA)

 1   0.000        0.689        3   0.076       12.411        4  15.240        5.516
 2   0.008       27.579

 -----------
 - GENERAL -
 -----------

MAX TIME STEP (S):         0.000100       PRINT STEP (S):           0.000000       MAX RELATIVE
ERROR (-):     0.00200
PRINT OPTIONS:          1 2 1 0 1 1       STORE OPTION:                     0       CONSTANT-
PRESSURE OPTION:         0
GRADIENT MODEL: CHAMBRAGE

 ----------
 - RECOIL -
 ----------

RECOIL OPTION:                   0       TYPE:                                    RECOILING
WEIGHT (KG):           0.

 ----------
 - PRIMER -
 ----------

TYPE: BLK POWDER                GAMMA (-):         1.2500       FORCE (J/KG):      286950.
COVOLUME (M3/KG):   1.0838E-03  FLAME TEMP (K):    2000.0       WEIGHT (KG):      0.006985
1M30 GEN GRAIN                                     IBHVG2.506    DATE            TIME
```

```
 ------------
 - CHARGE 1 -
 ------------

TYPE: BLK POWDER        GRAINS:   16739.     CORD     WEIGHT (KG):   0.6804
EROSIVE COEFF (-):   0.000000     CHARGE IGN CODE:   0   CHARGE IGN AT (S): 0.00000E+00
GRAIN LENGTH (M):    0.005029     GRAIN DIAMETER (M):   0.002489

PROPERTIES AT LAYER BOUNDARIES OF END SURFACES     PROPERTIES AT LAYER BOUNDARIES OF LAT SURFACES
                        1ST     2ND     3RD     4TH         1ST     2ND     3RD     4TH
AT DEPTH (M):          ------ ------  ------  0.00000     ------  ------  ------  0.00000
ADJACENT LAYER WT %:   ------ ------  ------  100.000     ------  ------  ------  100.000
DENSITY (KG/M3):       ------ ------  ------ 1660.794     ------  ------  ------ 1660.794
GAMMA (-):             ------ ------  ------   1.2500     ------  ------  ------   1.2500
FORCE (J/KG):          ------ ------  ------  286950.     ------  ------  ------  286950.
COVOLUME (M3/KG):      ------ ------  ------ 1.2645E-03   ------  ------  ------ 1.2645E-03
FLAME TEMP (K):        ------ ------  ------   2000.0     ------  ------  ------   2000.0
BURNING RATE EXPS:     ------ ------  ------   0.0000     ------  ------  ------   0.0000
BURNING RATE COEFFS:   ------ ------  ------   0.5080     ------  ------  ------   0.5080


 ------------
 - CHARGE 2 -
 ------------

TYPE: M30 LOT UNKNOWN           GRAINS:          1.   GEN  WEIGHT (KG):     22.0000
EROSIVE COEFF (-): 0.000000   CHARGE IGN CODE:      0       CHARGE IGN AT (S):  0.00000E+00

 I  DEPTH (M)   SURFACE (M2)    I  DEPTH (M)   SURFACE (M2)    I  DEPTH (M)   SURFACE (M2)
 1  0.00000000   13.872000      8  0.00065000   11.534000     15  0.00082000   5.326700
 2  0.00025000   17.844000      9  0.00067000   10.352000     16  0.00083000   4.169800
 3  0.00058000   22.427000     10  0.00069000    8.852000     17  0.00085000   3.250600
 4  0.00059000   17.099001     11  0.00071000    7.545400     18  0.00090000   1.744100
 5  0.00060000   15.662000     12  0.00072000    6.940200     19  0.00094000   0.786720
 6  0.00063000   12.893000     13  0.00073000    6.701700     20  0.00099000   0.000000
 7  0.00064000   12.184000     14  0.00075000    6.353400


PROPERTIES AT LAYER BOUNDARIES OF PERF SURFACES  PROPERTIES AT LAYER BOUNDARIES OF END SURFACES
                        1ST     2ND     3RD     4TH         1ST     2ND     3RD     4TH
AT DEPTH (M):          ------  ------  ------  0.00000     ------  ------  ------  0.00000
ADJACENT LAYER WT %:  ------  ------  ------  100.000     ------  ------  ------  100.000
DENSITY (KG/M3):       ------  ------  ------ 1680.170     ------  ------  ------ 1680.170
GAMMA (-):             ------  ------  ------   1.2441     ------  ------  ------   1.2441
FORCE (J/KG):          ------  ------  ------ 1075693.     ------  ------  ------ 1075693.
COVOLUME (M3/KG):      ------  ------  ------ 1.0275E-03   ------  ------  ------ 1.0275E-03
FLAME TEMP (K):        ------  ------  ------   3012.0     ------  ------  ------   3012.0
MEAN PRESSURES (MPA): ------  ------  ------   41.369     ------  ------  ------   41.369
MEAN PRESSURES (MPA): ------  ------  ------   68.948     ------  ------  ------   68.948
MEAN PRESSURES (MPA): ------  ------  ------   82.737     ------  ------  ------   82.737
MEAN PRESSURES (MPA): ------  ------  ------  275.790     ------  ------  ------  275.790
BURNING RATES (M/S):  ------  ------  ------  0.05080     ------  ------  ------  0.05080
BURNING RATES (M/S):  ------  ------  ------  0.06502     ------  ------  ------  0.06502
BURNING RATES (M/S):  ------  ------  ------  0.06985     ------  ------  ------  0.06985
BURNING RATES (M/S):  ------  ------  ------  0.15088     ------  ------  ------  0.15088

                         PROPERTIES AT LAYER BOUNDARIES OF  LAT SURFACES
                                1ST         2ND         3RD         4TH

   AT DEPTH (M):               ------      ------      ------     0.00000
   ADJACENT LAYER WT %:        ------      ------      ------     100.000
   DENSITY (KG/M3):            ------      ------      ------    1680.170
   GAMMA (-):                  ------      ------      ------      1.2441
   FORCE (J/KG):               ------      ------      ------    1075693.
   COVOLUME (M3/KG):           ------      ------      ------  1.0275E-03
   FLAME TEMP (K):             ------      ------      ------      3012.0
   MEAN PRESSURES (MPA):       ------      ------      ------      41.369
   MEAN PRESSURES (MPA):       ------      ------      ------      68.948
   MEAN PRESSURES (MPA):       ------      ------      ------      82.737
   MEAN PRESSURES (MPA):       ------      ------      ------     275.790
   BURNING RATES (M/S):        ------      ------      ------     0.05080
```

```
   BURNING RATES (M/S):       ------      ------      ------     0.06502
   BURNING RATES (M/S):       ------      ------      ------     0.06985
   BURNING RATES (M/S):       ------      ------      ------     0.15088
1M30 GEN GRAIN                                             IBHVG2.506     DATE             TIME

      TRAJECTORY VARIABLES: / 1/  TRAJ 1  TIME          TIME
                            / 2/  TRAJ 1  TRAV          TRAV
                            / 3/  TRAJ 1  Z(2)          FRAC BRND
                            / 4/  TRAJ 1  DB-P(2)       DB BRND CM
                            / 5/  TRAJ 1  SRF(2)        SRF (CM2)

    / 1/        / 2/        / 3/        / 4/        / 5/
0 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.13872E+06
  0.10000E+00 0.00000E+00 0.45769E-03 0.00000E+00 0.13879E+06
  0.12383     0.00000E+00 0.62582E-03 0.00000E+00 0.13881E+06
 SHOT-START PRESSURE ACHIEVED
  0.20000     0.48070E-06 0.12806E-02 0.00000E+00 0.13891E+06
  0.30000     0.61407E-05 0.23792E-02 0.00000E+00 0.13908E+06
  0.40000     0.24263E-04 0.37185E-02 0.00000E+00 0.13928E+06
  0.50000     0.62502E-04 0.52783E-02 0.00000E+00 0.13951E+06
  0.60000     0.12851E-03 0.70454E-02 0.00000E+00 0.13977E+06
  0.70000     0.22963E-03 0.90103E-02 0.00000E+00 0.14006E+06
  0.80000     0.37256E-03 0.11166E-01 0.00000E+00 0.14038E+06
  0.90000     0.56312E-03 0.13508E-01 0.00000E+00 0.14073E+06
  1.00000     0.80602E-03 0.16032E-01 0.00000E+00 0.14110E+06
   1.1000     0.11047E-02 0.18735E-01 0.00000E+00 0.14150E+06
   1.2000     0.14610E-02 0.21614E-01 0.00000E+00 0.14192E+06
   1.3000     0.18757E-02 0.24670E-01 0.00000E+00 0.14237E+06
   1.4000     0.23475E-02 0.27900E-01 0.00000E+00 0.14284E+06
   1.5000     0.28740E-02 0.31303E-01 0.00000E+00 0.14334E+06
   1.6000     0.34513E-02 0.34881E-01 0.00000E+00 0.14386E+06
   1.7000     0.40743E-02 0.38633E-01 0.00000E+00 0.14440E+06
   1.8000     0.47370E-02 0.42559E-01 0.00000E+00 0.14496E+06
   1.9000     0.54322E-02 0.46661E-01 0.00000E+00 0.14555E+06
   2.0000     0.61526E-02 0.50940E-01 0.00000E+00 0.14616E+06
   2.1000     0.68904E-02 0.55397E-01 0.00000E+00 0.14679E+06
   2.2000     0.76379E-02 0.60033E-01 0.00000E+00 0.14745E+06
   2.3000     0.83929E-02 0.64851E-01 0.00000E+00 0.14813E+06
   2.4000     0.91731E-02 0.69853E-01 0.00000E+00 0.14883E+06
   2.4500     0.95798E-02 0.72423E-01 0.00000E+00 0.14919E+06
 PROPELLANT 1 BURNED OUT
   2.5000     0.10002E-01 0.75040E-01 0.00000E+00 0.14955E+06
   2.6000     0.10902E-01 0.80416E-01 0.00000E+00 0.15030E+06
   2.7000     0.11899E-01 0.85983E-01 0.00000E+00 0.15107E+06
   2.8000     0.13018E-01 0.91745E-01 0.00000E+00 0.15186E+06
   2.9000     0.14286E-01 0.97704E-01 0.00000E+00 0.15267E+06
   3.0000     0.15732E-01 0.10386     0.00000E+00 0.15351E+06
   3.1000     0.17384E-01 0.11023     0.00000E+00 0.15437E+06
   3.2000     0.19272E-01 0.11680     0.00000E+00 0.15525E+06
   3.3000     0.21428E-01 0.12358     0.00000E+00 0.15616E+06
   3.4000     0.23885E-01 0.13057     0.00000E+00 0.15709E+06
   3.5000     0.26678E-01 0.13779     0.00000E+00 0.15804E+06
   3.6000     0.29843E-01 0.14522     0.00000E+00 0.15901E+06
   3.7000     0.33416E-01 0.15287     0.00000E+00 0.16001E+06
   3.8000     0.37436E-01 0.16075     0.00000E+00 0.16103E+06
   3.9000     0.41945E-01 0.16884     0.00000E+00 0.16208E+06
   4.0000     0.46984E-01 0.17714     0.00000E+00 0.16314E+06
   4.1000     0.52596E-01 0.18562     0.00000E+00 0.16421E+06
   4.2000     0.58827E-01 0.19431     0.00000E+00 0.16531E+06
   4.3000     0.65723E-01 0.20323     0.00000E+00 0.16643E+06
   4.4000     0.73332E-01 0.21244     0.00000E+00 0.16758E+06
   4.5000     0.81704E-01 0.22195     0.00000E+00 0.16875E+06
1M30 GEN GRAIN                                     IBHVG2.506     DATE             TIME

      TRAJECTORY VARIABLES: / 1/  TRAJ 1  TIME          TIME
                            / 2/  TRAJ 1  TRAV          TRAV
                            / 3/  TRAJ 1  Z(2)          FRAC BRND
                            / 4/  TRAJ 1  DB-P(2)       DB BRND CM
                            / 5/  TRAJ 1  SRF(2)        SRF (CM2)

    / 1/        / 2/        / 3/        / 4/        / 5/
```

```
0  4.6000     0.90879E-01 0.23176     0.00000E+00 0.16996E+06
   4.7000     0.10089     0.24189     0.00000E+00 0.17119E+06
   4.8000     0.11177     0.25233     0.00000E+00 0.17246E+06
   4.9000     0.12356     0.26310     0.00000E+00 0.17375E+06
   5.0000     0.13629     0.27419     0.00000E+00 0.17508E+06
   5.1000     0.14998     0.28562     0.00000E+00 0.17643E+06
   5.2000     0.16469     0.29739     0.00000E+00 0.17781E+06
   5.3000     0.18044     0.30949     0.00000E+00 0.17912E+06
   5.4000     0.19725     0.32193     0.00000E+00 0.18038E+06
   5.5000     0.21518     0.33471     0.00000E+00 0.18167E+06
   5.6000     0.23425     0.34782     0.00000E+00 0.18297E+06
   5.7000     0.25449     0.36128     0.00000E+00 0.18431E+06
   5.8000     0.27593     0.37508     0.00000E+00 0.18566E+06
   5.9000     0.29861     0.38922     0.00000E+00 0.18704E+06
   6.0000     0.32256     0.40371     0.00000E+00 0.18845E+06
   6.1000     0.34780     0.41854     0.00000E+00 0.18987E+06
   6.2000     0.37437     0.43372     0.00000E+00 0.19132E+06
   6.3000     0.40230     0.44924     0.00000E+00 0.19279E+06
   6.4000     0.43160     0.46511     0.00000E+00 0.19428E+06
   6.5000     0.46232     0.48132     0.00000E+00 0.19579E+06
   6.6000     0.49447     0.49788     0.00000E+00 0.19732E+06
   6.7000     0.52808     0.51477     0.00000E+00 0.19887E+06
   6.8000     0.56317     0.53201     0.00000E+00 0.20044E+06
   6.9000     0.59978     0.54958     0.00000E+00 0.20203E+06
   7.0000     0.63791     0.56748     0.00000E+00 0.20364E+06
   7.1000     0.67759     0.58572     0.00000E+00 0.20526E+06
   7.2000     0.71885     0.60428     0.00000E+00 0.20690E+06
   7.3000     0.76170     0.62316     0.00000E+00 0.20855E+06
   7.4000     0.80615     0.64236     0.00000E+00 0.21022E+06
   7.5000     0.85224     0.66188     0.00000E+00 0.21190E+06
   7.6000     0.89996     0.68171     0.00000E+00 0.21359E+06
   7.7000     0.94935     0.70184     0.00000E+00 0.21530E+06
   7.8000      1.0004     0.72228     0.00000E+00 0.21702E+06
   7.9000      1.0532     0.74300     0.00000E+00 0.21875E+06
   8.0000      1.1076     0.76402     0.00000E+00 0.22049E+06
   8.1000      1.1638     0.78532     0.00000E+00 0.22224E+06
   8.2000      1.2217     0.80691     0.00000E+00 0.22400E+06
   8.2912      1.2760     0.82480     0.00000E+00 0.17283E+06
 LOCAL PRESSURE MAX DETECTED
   8.3000      1.2813     0.82626     0.00000E+00 0.16989E+06
   8.4000      1.3427     0.84190     0.00000E+00 0.15340E+06
   8.5000      1.4057     0.85619     0.00000E+00 0.14170E+06
   8.6000      1.4705     0.86930     0.00000E+00 0.13003E+06
   8.7000      1.5371     0.88134     0.00000E+00 0.12094E+06
   8.8000      1.6052     0.89250     0.00000E+00 0.11305E+06
   8.9000      1.6751     0.90286     0.00000E+00 0.10572E+06
   9.0000      1.7466     0.91242     0.00000E+00  97076.
   9.1000      1.8196     0.92104     0.00000E+00  88000.
   9.2000      1.8943     0.92880     0.00000E+00  80102.
   9.3000      1.9705     0.93576     0.00000E+00  72518.
1M30 GEN GRAIN                                   IBHVG2.506     DATE              TIME

      TRAJECTORY VARIABLES: / 1/  TRAJ 1  TIME          TIME
                            / 2/  TRAJ 1  TRAV          TRAV
                            / 3/  TRAJ 1  Z(2)          FRAC BRND
                            / 4/  TRAJ 1  DB-P(2)       DB BRND CM
                            / 5/  TRAJ 1  SRF(2)        SRF (CM2)

    / 1/        / 2/        / 3/        / 4/        / 5/
0  9.4000      2.0483     0.94205     0.00000E+00  67807.
   9.5000      2.1276     0.94800     0.00000E+00  65556.
   9.6000      2.2083     0.95370     0.00000E+00  63542.
   9.7000      2.2904     0.95918     0.00000E+00  61864.
   9.8000      2.3740     0.96445     0.00000E+00  60207.
   9.9000      2.4589     0.96951     0.00000E+00  58570.
  10.0000      2.5452     0.97437     0.00000E+00  56952.
   10.100      2.6328     0.97904     0.00000E+00  55354.
   10.200      2.7217     0.98353     0.00000E+00  53776.
   10.300      2.8119     0.98763     0.00000E+00  44987.
   10.400      2.9033     0.99091     0.00000E+00  38183.
   10.500      2.9959     0.99374     0.00000E+00  33424.
```

```
  10.600      3.0897     0.99621     0.00000E+00  30030.
  10.700      3.1847     0.99840     0.00000E+00  26995.
  10.778      3.2593      1.0000     0.00000E+00 0.00000E+00
 PROPELLANT 2 BURNED OUT
  10.800      3.2808      1.0000     0.00000E+00 0.00000E+00
  10.900      3.3780      1.0000     0.00000E+00 0.00000E+00
  11.000      3.4762      1.0000     0.00000E+00 0.00000E+00
  11.100      3.5756      1.0000     0.00000E+00 0.00000E+00
  11.200      3.6759      1.0000     0.00000E+00 0.00000E+00
  11.300      3.7772      1.0000     0.00000E+00 0.00000E+00
  11.400      3.8795      1.0000     0.00000E+00 0.00000E+00
  11.500      3.9827      1.0000     0.00000E+00 0.00000E+00
  11.600      4.0869      1.0000     0.00000E+00 0.00000E+00
  11.700      4.1920      1.0000     0.00000E+00 0.00000E+00
  11.800      4.2979      1.0000     0.00000E+00 0.00000E+00
  11.900      4.4047      1.0000     0.00000E+00 0.00000E+00
  12.000      4.5123      1.0000     0.00000E+00 0.00000E+00
  12.100      4.6207      1.0000     0.00000E+00 0.00000E+00
  12.200      4.7300      1.0000     0.00000E+00 0.00000E+00
  12.300      4.8400      1.0000     0.00000E+00 0.00000E+00
  12.400      4.9507      1.0000     0.00000E+00 0.00000E+00
  12.444      5.0000      1.0000     0.00000E+00 0.00000E+00
 PROJECTILE EXIT
1M30 GEN GRAIN                                    IBHVG2.506     DATE             TIME


 CONDITIONS AT:           PMAX   MUZZLE

 TIME (MS):             8.291   12.444
 TRAVEL (M):           1.2760   5.0000
 VELOCITY (M/S)        603.40  1114.67
 ACCELERATION (G):     17721.    7481.
 BREECH PRESS (MPA): 227.1182 110.2084
 MEAN PRESS (MPA):   211.3120  98.1963
 BASE PRESS (MPA):   164.6090  76.2674
 MEAN TEMP (K):         2728.    2267.
 Z CHARGE 1 (-):        1.000    1.000
 Z CHARGE 2 (-):        0.825    1.000

     ENERGY BALANCE SUMMARY               JOULE          %

 TOTAL CHEMICAL:                        97707672.      100.00

 (1) INTERNAL GAS:                      73838192.       75.57
 (2) WORK AND LOSSES:                   23869482.       24.43

     (A) PROJECTILE KINETIC:            14652512.       15.00
     (B) GAS KINETIC:                    4565768.        4.67
     (C) PROJECTILE ROTATIONAL:             7378.        0.01
     (D) FRICTIONAL WORK TO TUBE:              0.        0.00
     (E) OTHER FRICTIONAL WORK:          1537771.        1.57
     (F) WORK DONE AGAINST AIR:           145025.        0.15
     (G) HEAT CONVECTED TO BORE:         2961028.        3.03
     (H) RECOIL ENERGY:                        0.        0.00


 LOADING DENSITY (KG/M3):      313.566
 CHARGE WT/PROJECTILE WT:        0.962
 PIEZOMETRIC EFFICIENCY:         0.479
 EXPANSION RATIO:                2.862
```

Appendix H. Source Code for Generic Grain Program

```
C
C   GENERIC GRAIN SURFACE AND VOLUME CALCULATOR
C
      COMMON /CONBLK/
     $ PI,PI2,PI3,PI4,RT3

      DIMENSION CHAR(80),VAL(7,20),ITYPE(20),A(4,20),S(3,20)

      PI = 3.1415926
      RT3 = 1.7320508

      PI2 = PI / 2.0
      PI3 = PI / 3.0
      PI4 = PI / 4.0

      XMAXLN=0.0
   10 DO 20 I=1,80
   20    CHAR(I)=' '
   30 READ(5,100,END=40,ERR=40) (CHAR(I),I=1,80)
  100 FORMAT(80A1)
      IF (CHAR(1) .EQ. 'c' .OR. CHAR(1) .EQ. 'C') GO TO 10
      WRITE(2,100) (CHAR(I),I=1,80)
      WRITE(6,200) (CHAR(I),I=1,80)
  200 FORMAT(' ',80A1)
      GO TO 10
   40 REWIND 2
      J=0
   50 J=J+1
      READ (2,300,END=60,ERR=60) ITYPE(J),(VAL(I,J),I=1,7)
  300 FORMAT(I3,F7.0,6F10.0)
      GO TO 50
   60 J=J-1
      DO 70 K=1,J
         IF (ITYPE(K) .EQ. 1 .OR. ITYPE(K) .EQ. 2) THEN
C  TYPE 1 TRAPEZOID OR TYPE 2 TRAPEZOID
            IF (VAL(2,K) .LE. 0.0 .OR. VAL(7,K) .LE. 0.0) GOTO 80
            IF (VAL(7,K) .GT. XMAXLN) XMAXLN=VAL(7,K)
         ELSE IF (ITYPE(K) .EQ. 3) THEN
C  CIRCULAR GRAIN SLIVER
            IF (VAL(3,K) .LE. 0.0 .OR. VAL(4,K) .LE. 0.0) GO TO 80
            IF (VAL(5,K) .LE. 0.0) GO TO 80
            IF (VAL(5,K) .GT. XMAXLN) XMAXLN=VAL(5,K)
         ELSE IF (ITYPE(K) .EQ. 4) THEN
C  TRIANGULAR INNER SLIVER
            IF (VAL(2,K) .LE. 0.0 .OR. VAL(3,K) .LE. 0.0) GO TO 80
            IF (VAL(4,K) .LE. 0.0) GO TO 80
            IF (VAL(4,K) .GT. XMAXLN) XMAXLN=VAL(4,K)
            DO 65 I=1,3
   65          S(I,K)=VAL(2,K)+VAL(3,K)
            CALL GENISL(S(1,K),A(1,K),0.0,0.0,0.0,B,K,0)
         ELSE IF (ITYPE(K) .EQ. 5) THEN
```

```
C  ITERATION DATA
            IF (VAL(1,K) .LE. 0.0) GO TO 80
            IF (VAL(2,K) .LE. 0.0) VAL(2,K)=1.0
            DELTA=VAL(1,K)
C  UNKNOWN
         ELSE
            GO TO 80
         ENDIF
         IF (VAL(1,K) .LE. 0.0) VAL(1,K)=1.0
   70    CONTINUE
      DB=0.0
      VINIT=0.0
      ITER=INT(XMAXLN/DELTA)+1
      WRITE(6,500)
      WRITE(7,500)
  500 FORMAT(//'  Z BRNED     DEPTH BRNED       VOL       SURF',
     1   10x,'SFE',10x,'SFP',10x,'SFL'/)
      DO 75 K=1,ITER
         SURF=0.0
         VOL=0.0
         SFE=0.0
         SFP=0.0
         SFL=0.0
         DO 72 I=1,J
            SURFE=0.0
            SURFP=0.0
            SURFL=0.0
            V=0.0
            R1=0.0
            R2=0.0
            IF (ITYPE(I) .EQ. 1) THEN
               XL=VAL(7,I)-2.0*DB
               IF(XL .LE. 0.0) GO TO 72
               IF (VAL(4,I) .GT. 0.0) R1=0.5*VAL(4,I)+DB
               IF (VAL(6,I) .GT. 0.0) R2=0.5*VAL(6,I)+DB
               CALL TYPOS1(VAL(2,I),DB,VAL(3,I),R1,VAL(5,I),R2,
     1            SURFE,SURFP,SURFL,B)
               V=SURFE*XL*VAL(1,I)
               SURFE=2.0*SURFE*VAL(1,I)
               SURFP=SURFP*XL*VAL(1,I)
               SURFL=SURFL*XL*VAL(1,I)
            ELSE IF (ITYPE(I) .EQ. 2) THEN
               XL=VAL(7,I)-2.0*DB
               IF(XL .LE. 0.0) GO TO 72
               IF (VAL(4,I) .GT. 0.0) R1=0.5*VAL(4,I)+DB
               IF (VAL(6,I) .GT. 0.0) R2=0.5*VAL(6,I)+DB
               CALL TYPOS2(VAL(2,I),DB,VAL(3,I),R1,VAL(5,I),R2,
     1            SURFE,SURFP,SURFL,B)
               V=SURFE*XL*VAL(1,I)
               SURFE=2.0*SURFE*VAL(1,I)
               SURFP=SURFP*XL*VAL(1,I)
               SURFL=SURFL*XL*VAL(1,I)
            ELSE IF (ITYPE(I) .EQ. 3) THEN
               IF (VAL(2,I) .GT. 0.0) R1=0.5*VAL(2,I)+DB
               R2=0.5*VAL(3,I)-DB
               XL=VAL(5,I)-2.0*DB
               IF(R1 .GE. R2 .OR. XL .LE. 0.0) GO TO 72
```

```
              SURFE=(R2*R2-R1*R1)*VAL(4,I)*0.5
              SURFP=R1*VAL(4,I)
              SURFL=R2*VAL(4,I)
              V=SURFE*XL*VAL(1,I)
              SURFE=2.0*SURFE*VAL(1,I)
              SURFP=SURFP*XL*VAL(1,I)
              SURFL=SURFL*XL*VAL(1,I)
           ELSE IF (ITYPE(I) .EQ. 4) THEN
              XL=VAL(4,I)-2.0*DB
              IF (XL .LE. 0.0) GO TO 72
              PD=VAL(2,I)+2.0*DB
              CALL GENISL(S(1,I),A(1,I),PD,SURFE,SURFP,B,I,1)
              V=0.5*SURFE*XL*VAL(1,I)
              SURFE=SURFE*VAL(1,I)
              SURFP=SURFP*XL*VAL(1,I)
           ENDIF
           SFE=SFE+SURFE
           SFP=SFP+SURFP
           SFL=SFL+SURFL
           SURF=SURF+(SURFE+SURFP+SURFL)*VAL(2,J)
           VOL=VOL+V*VAL(2,J)
   72      CONTINUE
        IF (K.EQ.1) VINIT=VOL
        Z=1.0-VOL/VINIT
        WRITE(6,600) Z,DB,VOL,SURF,SFE,SFP,SFL
        WRITE(7,600) Z,DB,VOL,SURF,SFE,SFP,SFL
  600   FORMAT(7E13.5)
        IF (VOL .LE. 0.0 .OR. SURF .LE. 0.0) GO TO 78
   75   DB=DB+DELTA
   78 STOP
   80 WRITE(6,1000) K,ITYPE(K),(VAL(I,K),I=1,6)
 1000 FORMAT(' ERROR... INPUT CARD ',I3/
     1   ' DATA TYPE',I3/' VALUES=',1P6E12.4)
      STOP
      END
      SUBROUTINE TYPOS1(WALL,DB,WA,RADA,WB,RADB,END,SP,SL,B)
C
C  GENERALIZED OUTER SLIVER ROUTINE FOR COMPUTING CURRENT AREA AND EDGES
C          (OUTER EDGE MUST BE PERPENDICULAR TO SIDES)
C
C (I)    WALL = OUTER EDGE (STRAIGHT-LINE MEASUREMENT)
C (I)    DB   = DEPTH BURNED INTO OUTER (LATERAL) SURFACE
C (I)    WA   = PERPENDICULAR FROM OUTER EDGE TO CENTER OF ONE PERF
C (I)    RADA = CURRENT RADIUS OF PERFORATION AT DEPTH WA
C (I)    WB   = PERPENDICULAR FROM OUTER EDGE TO CENTER OF OTHER PERF
C (I)    RADB = CURRENT RADIUS OF PERFORATION AT DEPTH WB
C (O)    END  = CURRENT END SURFACE AREA OF REMAINING SLIVER
C (O)    SP   = CURRENT LINEAR PERFORATION EDGE OF REMAINING SLIVER END
C (O)    SL   = CURRENT LINEAR LATERAL EDGE OF REMAINING SLIVER END
C (O)    B    = REMAINING FRACTION OF ORIGINAL MAXIMUM SLIVER END AREA
C
C     ASSUMPTIONS:
C            1) REGULAR RECTANGULAR OR TRAPEZOIDAL SLIVER
C            2) ZERO, ONE, OR TWO PERFS PRESENT (MAY BE UNEQUAL RADII)
C
C     (VARIOUS CHECKS TO ASSURE SIN AND/OR COS OF SMALL ANGLES DO NOT
C      STRAY OFF FAR ENOUGH TO GIVE SPURIOUS CALCULATED VALUES OF XS,XL)
```

```
C
      COMMON /CONBLK/
     $ PI,PI2,PI3,PI4,RT3
C
      SL = 0.
      SP = 0.
      END = 0.
      B = 0.
C
C        QUICK CHECK FOR BURNOUT
C
      IF ( DB .GE. WA .AND. DB .GE. WB ) RETURN
      IF ( WALL .LE. 0. ) RETURN
C
      RS = 0.
      RL = 0.
      WS = 0.
      WL = 0.
      ARCS = 0.
      ARCL = 0.
      ALPH1 = 0.
      ALPH2 = 0.
      ALPH3 = 0.
      BETA1 = 0.
      BETA2 = 0.
      XS = 0.
      XL = 0.
      S = 0.
      AREA = 0.
C
C        SET RS,WS TO SHORT WALL RADIUS AND CURRENT DEPTH
      RS = RADA
      RL = RADB
      WS = WA - DB
      WL = WB - DB
      IF ( WL .GE. WS ) GO TO 10
      RS = RADB
      RL = RADA
      WS = WL
      WL = WA - DB
C
   10 WD = WL - WS
      END0 = 0.5 * WALL * ( WA + WB )
      END = END0
      DIST = SQRT( WALL * WALL + WD * WD )
      IF ( RS + RL .GT. DIST ) GO TO 40
C
C        NO PERF-TO-PERF BURN-THROUGH
C
      IF ( RL .LE. 0. ) GO TO 30
C       LONG-SIDE PERF CALCULATIONS
      IF ( WL .LE. WD * RL / DIST ) GO TO 100
   15 ARCL = ASIN( WALL / DIST )
   20 IF ( WL .GE. RL ) GO TO 30
C        CALCULATE INTERSECTION BETWEEN LATERAL SURFACE AND LS PERF
      XL = SQRT( RL * RL - WL * WL )
      ARCL = ARCL - ACOS( WL / RL )
```

```
      END = END - 0.5 * WL * XL
   30 IF ( RS .GT. 0. .AND. WL .GT. WD - RS * WD / DIST ) GO TO 32
      IF ( WS .LT. 0.) END = END + 0.5 * WALL * WS * WS / WD
C        GENERALIZED END-OF-CALCULATION REDUCTION FOR END AREA AND ARCL
   33 END = END - WALL * DB
   31 ARCL = ARCL - BETA1
      GO TO 90
C        SHORT-SIDE PERF CALCULATIONS
   32 ARCS = PI2 + ACOS( WALL / DIST ) - ALPH1
      IF ( RS .LE. WALL ) GO TO 320
      IF ( RL .LT. WD - SQRT( RS * RS - WALL * WALL )) GO TO 35
  320 IF ( WS .LE. 0. ) GO TO 34
  325 IF ( WS .GE. RS ) GO TO 33
C        CHECK FOR BURNOUT; COMPARE ORIG ARC TO REMAINING SS PERF ARC
      IF ( ARCS .LT. ACOS( WS / RS )) GO TO 100
C        CALCULATE INTERSECTION OF LAT SURF WITH SS PERF
      XS = SQRT( RS * RS - WS * WS )
C        IF LOWER SECTION BURNED OUT, MAXIMUM XS WILL BE WALL LENGTH
      IF ( XS .GT. WALL ) XS = WALL
      ARCS = ARCS - ASIN( XS / RS )
      END = END - 0.5 * WS * XS
      GO TO 33
   34 IF ( -WS .LT. RS * WD / DIST ) GO TO 340
C        SHORT-SIDE PERF CONSUMED BY LATERAL SURFACE
      ARCS = 0
      END = 0.5 * WL * WL * WALL / WD
      GO TO 31
C        LAT SURFACE BURNED PAST SS PERF CENTER
  340 S = WALL - SQRT( RS * RS - WS * WS )
      XS = WALL * WL / WD - S
      ARCS = ARCS - ( PI2 + ASIN( -WS / RS ))
      END = 0.5 * WALL * WD - 0.5 * ( -WS ) * ( WALL + S )
      GO TO 31
C        SS PERF BURNED THRU TO OPPOSITE SIDE
C          CHECK ABOVE OR BELOW PERF CENTER
   35 IF ( WS .LT. 0. ) GO TO 340
C        SS PERF BURNED THRU TO OPPOSITE SIDE - LAT BELOW PERF CTR
      S = SQRT( RS * RS - WALL * WALL )
      IF ( WS .LT. RS ) GO TO 38
      ARCS = ARCS - 2.0 * ACOS( WALL / RS )
      END = END - WALL * S
      GO TO 33
C       LAT SURF BETWEEN SS PERF CTR AND PERF RADIUS
   38 IF ( WS .GT. S ) GO TO 39
C        LAT SURF WITHIN LOWER OPPOSITE WALL OCCLUSION
      XS = WALL
      ARCS = ARCS - PI2 - ACOS( WALL / RS )
      END = 0.5 * WALL * ( WD - S )
      GO TO 31
C        LAT SURF INTERSECTS SS PERF BELOW OPPOSITE WALL OCCLUSION
   39 XS = SQRT( RS * RS - WS * WS )
      ARCS = ARCS - ACOS( WS / RS ) - 2.0 * ACOS( WALL / RS )
      END = END - WALL * S - 0.5 * XS * WS
      GO TO 33
C
C        BURNED THROUGH DISTANCE BETWEEN PERF CTRS (ALONG "DIAG" LINE)
C
```

```
   40 IF ( RL .GE. WALL ) S = SQRT( RL * RL - WALL * WALL )
      IF ( RL .GE. WALL .AND. RS .LE. S - WD ) RS = 0.
      IF ( RS .GT. 0. ) GO TO 42
      IF ( WL .LE. SQRT( RL * RL - WALL * WALL )) GO TO 100
C       ONLY LONG-SIDE PERF EXISTS .OR. SS PERF HAS BEEN ECLIPSED
C         CALCULATE BURNED AREA ALONG DIAGONAL
      BETA1 = ASIN( WALL / DIST ) - ASIN( WALL / RL )
      AREA = 0.5 * DIST * RL * SIN( BETA1 )
      GO TO 15
   42 IF ( RL .GT. 0. ) GO TO 44
C       ONLY SHORT-SIDE PERF EXISTS, RS>DIST, RS>WALL
C         SHORT-SIDE PERF HAS BURNED DIAGONAL AWAY
C         CHECK FOR COMPLETE BURN-OUT
      IF ( WL .LE. WD + SQRT( RS * RS - WALL * WALL )) GO TO 100
      ARCS = PI2 - ACOS( WALL / RS )
      END = END - 0.5 * WALL * ( WD + SQRT( RS * RS - WALL * WALL ))
      IF ( WS .GE. RS ) GO TO 33
C       INTERSECTION OF LAT SURF WITH SS PERF
      XS = SQRT( RS * RS - WS * WS )
      END = END - 0.5 * XS * WS
      ARCS = ARCS - ACOS( WS / RS )
      GO TO 33
C       FIND TRIANGLE FORMED BY DIAGONAL AND INTERSECTION OF PERF RADII
   44 S = 0.5 * ( DIST + RS + RL )
      AREA = SQRT( S * ( S - DIST ) * ( S - RS ) * ( S - RL ))
      BETA1 = ASIN( 2.0 * AREA / DIST / RL )
      ARCL = ASIN( WALL / DIST )
      IF ( BETA1 .GE. ARCL ) GO TO 45
      IF ( WL .LE. RL * COS( ARCL - BETA1 )) GO TO 100
      ALPH1 = ASIN( 2.0 * AREA / DIST / RS )
C       SINCE "ASIN" ONLY RETURNS ANSWERS BETWEEN 0 AND PI/2, NEED TO
C         CHECK FOR SITUATIONS WHERE ALPH1 SHOULD BE GREATER THAN PI/2
      IF ( RL .GT. SQRT( RS * RS + DIST * DIST )) ALPH1 = PI - ALPH1
      GO TO 20
C       LONG-SIDE PERF ARC CONSUMED, DIAGONAL BURNED OUT
   45 ARCL = 0.
      BETA1 = 0.
      ALPH1 = ACOS( WALL / DIST )
      IF ( RS .GT. WALL ) ALPH1 = ALPH1 + ACOS( WALL / RS )
      AREA = 0.5 * RS * DIST * SIN( ALPH1 )
      GO TO 32
C
C       FINAL CALCULATIONS FOR END AREA AND BURNING ARCS
C
   90 END = END - AREA - 0.5 * ( ARCS * RS * RS + ARCL * RL * RL )
C       DUMP ANY NEGATIVE ROUND-OFF ERROR FORCING RESULTS<0
      IF ( END .LE. 0. ) GO TO 100
      B = END / END0
      SP = ARCS * RS + ARCL * RL
      SL = WALL - XS - XL
      IF ( WS .LT. 0. ) SL = WALL * WL / WD - XS - XL
      RETURN
C
C        SLIVER BURNED OUT
  100 END = 0.
      SL = 0.
      SP = 0.
```

```
      B = 0.
      RETURN
C
      END
      SUBROUTINE TYPOS2(WDTH,DB,SD1,PF1,SD2,PF2,AREA,SP,SLAT,B)
C
C  GENERALIZED OUTER SLIVER ROUTINE FOR COMPUTING CURRENT AREA AND EDGES
C    (INNER EDGE MUST BE A STRAIGHT LINE PERPENDICULAR TO SIDES)
C
C (I)    WDTH = OUTER BURNING EDGE
C (I)    DB   = DEPTH BURNED INTO OUTER SURFACE
C (I)    SD1  = PERPENDICULAR FROM CENTER OF ONE PERF TO OUTER EDGE
C (I)    PF1  = CURRENT RADIUS OF PERFORATION AT DEPTH SD1
C (I)    SD2  = PERPENDICULAR FROM CENTER OF OTHER PERF TO OUTER EDGE
C (I)    PF2  = CURRENT RADIUS OF PERFORATION AT DEPTH SD2
C (O)    AREA = CURRENT END SURFACE AREA OF REMAINING SLIVER
C (O)    SP   = CURRENT LINEAR PERFORATION EDGE OF REMAINING SLIVER END
C (O)    SLAT = CURRENT LINEAR LATERAL EDGE OF REMAINING SLIVER END
C (O)    B    = REMAINING FRACTION OF ORIGINAL MAXIMUM SLIVER END AREA
C
C     ASSUMPTIONS:
C            1) REGULAR RECTANGULAR OR TRAPEZOIDAL SLIVER
C            2) ZERO, ONE, OR TWO PERFS PRESENT (MAY BE UNEQUAL RADII)
C            3) SAME DEPTH BURNED ON ALL BURNING SURFACES
C
      COMMON /CONBLK/
     $ PI,PI2,PI3,PI4,RT3
C
      SLAT = 0.0
      SP = 0.0
      AREA = 0.0
      B = 0.0

      IF (WDTH .LE. 0.0) THEN
        PRINT *," ERROR... WDTH .LE. 0   WDTH=",WDTH
        GO TO 100
      ENDIF

      IF (SD1 .GT. SD2) THEN
        SL = SD1
        RL = PF1
        SS = SD2
        RS = PF2
      ELSE
        SL = SD2
        RL = PF2
        SS = SD1
        RS = PF1
      ENDIF
      DIAG = SQRT(WDTH*WDTH + (SL-SS)*(SL-SS))
      BSIDE = DB * WDTH / DIAG
      IF (BSIDE .GE. SL) THEN
        PRINT *," BURN .GE. DEPTH... BSIDE,SL=",BSIDE,SL
        GO TO 100
      ENDIF

C INITIALIZE
```

```
      IRS = 0
      OSBURN=0.0
      PSBURN=0.0
      PSAREA=0.0
      OLBURN=0.0
      PLBURN=0.0
      PLAREA=0.0
      CL = SL - BSIDE
      IF (BSIDE.GE.SS) THEN
        CS = 0.
      ELSE
        CS = SS - BSIDE
      ENDIF

      IF (RL.GT.0. .OR. RS.GT.0.) GO TO 10

C  NO PERFS
C  SHORT SIDE BURN-THROUGH?
      IF (BSIDE .GT. SS) THEN
        AREA = 0.5*CL*WDTH*CL/(SL-SS)
        SLAT = CL*DIAG/(SL-SS)
      ELSE
        AREA = 0.5*(CS+CL)*WDTH
        SLAT = DIAG
      ENDIF
      GO TO 100

   10 IF (RL .GT. 0.0) GO TO 20
C RS PERF GT 0, RL PERF=0

   11 BASE = WDTH
      CCS = CS
      CCL = CL
      DG = DIAG
      IF (CCS .EQ. 0.0) THEN
        DG = DIAG * CL/(SL-SS)
      ENDIF
   12 EM = 0.0
      X = 0.0
      Y = 0.0
      BASE2 = 0.0
      ANG = 0.0
      CCSS = 0.0
      IF (RS .GT. CCS) GO TO 15
      IF (RS .LE. BASE) THEN
        PSBURN = RS*PI2
        PSAREA = PI4*RS*RS
      ELSE
        ANG = ACOS(BASE/RS)
        PSBURN = RS*(PI2-ANG)
        PSAREA = 0.5*(PI2-ANG)*RS*RS + 0.5*BASE*RS*SIN(ANG)
      ENDIF
   14 CONTINUE
      IF (IRS .EQ. 2) GO TO 57
      IF (IRS .EQ. 1) GO TO 21
      GO TO 99
   15 IF (SL .EQ. SS) THEN
```

```
          ANG = ACOS(CCS/RS)
          PSBURN = RS * (PI2-ANG)
          PSAREA = 0.5*RS*RS*(PI2-ANG) + 0.5*CS*RS*SIN(ANG)
          IF (RS .GT. BASE) THEN
            ANG = ACOS(BASE/RS)
            PSBURN = PSBURN - RS*ANG
            PSAREA = PSAREA - 0.5*RS*RS*ANG + 0.5*BASE*RS*SIN(ANG)
          ENDIF
          OSBURN = SQRT(RS*RS - CCS*CCS)
          GO TO 14
        ENDIF
        CCSS = CCS
        IF (CCS .EQ. 0.0) THEN
          CCSS = SS - BSIDE
          BASE2 = BASE * CCL/(CCL-CCSS)
          IF (RS .LE. (BASE-BASE2)) GO TO 14
        ENDIF
        EM = (CCL-CCSS)/BASE
        X = -EM*CCSS + SQRT(EM*EM*RS*RS - CCSS*CCSS + RS*RS)
        X = X / (EM*EM + 1.0)
        IF (X.GE.BASE) THEN
          IF (IRS .EQ. 2) GO TO 57
          GO TO 100
        ENDIF
        Y = SQRT(RS*RS - X*X)
        IF (CCS .EQ. 0.0) THEN
          PSBURN = RS * ASIN(Y/RS)
          OSBURN = DG * Y/CCL
          PSAREA = 0.5*RS*RS*ASIN(Y/RS) - 0.5*Y*(BASE-BASE2)
          IF (RS .GT. BASE) THEN
            ANG = ACOS(BASE/RS)
            PSBURN = PSBURN - RS*ANG
            ABC = PI2 - ASIN(CCL/DG)
            BCA = PI - ANG - ABC
            PSAREA = PSAREA + 0.5*BASE*RS*SIN(ANG) - 0.5*RS*RS*ANG
       1       -0.5*(BASE-BASE2)*(BASE-BASE2)*SIN(ABC)/SIN(BCA)*SIN(ANG)
          ENDIF
        ELSE
          ANG = ASIN(Y/RS)
          PSBURN = RS*ANG
          OSBURN = DG * X/BASE
          PSAREA = 0.5*RS*RS*ANG + 0.5*CCS*RS*SIN(PI2-ANG)
          IF (RS .GT. BASE) THEN
            PSBURN = PSBURN - RS*ACOS(BASE/RS)
            PSAREA = PSAREA - 0.5*RS*RS*ACOS(BASE/RS)
       1                    + 0.5*BASE*SQRT(RS*RS-BASE*BASE)
          ENDIF
        ENDIF
        GO TO 14

   20   IF (RL.GT.0. .AND. RS.GT.0.) GO TO 30
C
C RL PERF GT 0, RS PERF=0
   21   BASE = WDTH
        CCS = CS
        CCL = CL
        DG = DIAG
```

```
22 AC = BASE
   IF (CCS .LE. 0.0) THEN
     AC = CCL*WDTH/(SL-SS)
     DG = CCL*DIAG/(SL-SS)
     IF (CCL .LE. RL .AND. AC .LE. RL) THEN
       IF (IRS.EQ.0) GO TO 100
       GO TO 99
     ENDIF
   ENDIF
   ANG = PI2
   THETA1 = 0.0
   THETA2 = 0.0
   THETA3 = 0.0
   A1 = 0.0
   A2 = 0.0
   A3 = 0.0
   S1 = 0.0
   S2 = 0.0
   X =  0.0
   Y = 0.0
   EM = 0.0
   AD = CCL*AC/DG
   IF (RL .GT. BASE) GO TO 23
   IF (AD .GE. RL) THEN
     PLBURN = ANG*RL
     OLBURN = 0.0
     PLAREA = 0.5*ANG*RL*RL
     GO TO 99
   ENDIF
   IF (AC .GT. RL) THEN
     THETA2 = ACOS(AD/RL)
     S2 = RL*SIN(THETA2)
   ELSE
     THETA2 = ASIN(BASE/DG)
     S2 = AC*BASE/DG
   ENDIF
   A2 = 0.5*S2*AD
   IF (CCL .GT. RL) THEN
     THETA1 = ACOS(AD/RL)
     S1 = RL*SIN(THETA1)
   ELSE
     THETA1 = ASIN((CCL-CCS)/DG)
     S1 = CCL*(CCL-CCS)/DG
   ENDIF
   A1 = 0.5*S1*AD
   GO TO 24
23 IF (CCL .LE. RL .AND. CCS .LE. SQRT(RL*RL-BASE*BASE)) THEN
     IF (IRS .GT. 0) GO TO 99
     GO TO 100
   ENDIF
   IF (AD .GT. RL) THEN
     THETA3 = ACOS(BASE/RL)
     A3 = 0.5 * BASE * RL*SIN(THETA3)
   ELSE IF (CCS .GT. SQRT(RL*RL - BASE*BASE)) THEN
     THETA3 = ACOS(BASE/RL)
     A3 = 0.5 * BASE * RL*SIN(THETA3)
     THETA2 = ACOS(AD/RL)
```

```
      S2 = RL * SIN(THETA2)
      A2 = 0.5 * AD * S2
      IF (CCL .GT. RL) THEN
        THETA1 = THETA2
        S1 = S2
      ELSE
        IF (AD .GT. CCL) THEN
          THETA1 = 0.0
        ELSE
          THETA1 = ACOS(AD/CCL)
        ENDIF
        S1 = CCL * SIN(THETA1)
      ENDIF
      A1 = 0.5 * AD * S1
    ELSE IF (CCS .GT. 0.) THEN
      AC = SQRT(CCS*CCS + BASE*BASE)
      THETA3 = ACOS(BASE / AC)
      A3 = 0.5 * BASE * CCS
      THETA2 = ACOS(AD / RL)
      THETA1 = ACOS(AD / AC)
      S2 = SQRT(RL*RL - AD*AD)
      S1 = SQRT(AC*AC - AD*AD)
      A2 = 0.5 * AD * (S1 + S2)
    ELSE
      THETA2 = ACOS(AD/AC)
      S2 = AC * SIN(THETA2)
      A2 = 0.5 * AD * AC
      THETA1 = ACOS(AD/RL)
      S1 = RL * SIN(THETA1)
      A1 = 0.5 * S1 * AD
    ENDIF
 24 PLAREA = A1+A2+A3+0.5*(PI2-THETA1-THETA2-THETA3)*RL*RL
    OLBURN = S1+S2
    PLBURN = (PI2-THETA1-THETA2-THETA3)*RL
    GO TO 99

 30 IF (RS+RL .GT. WDTH) GO TO 53
    IRS = 1
    GO TO 11
 53 IF (RL .LE. WDTH) GO TO 54
    IF (SQRT(RL*RL-WDTH*WDTH) .LT. RS) GO TO 54
    GO TO 21
 54 IF (RS .LE. WDTH) GO TO 55
    IF (SQRT(RS*RS-WDTH*WDTH) .LT. RL) GO TO 55
    GO TO 11
 55 XX = (RL*RL-RS*RS+WDTH*WDTH)/(2.0*WDTH)
    YY = SQRT(RL*RL-XX*XX)
    Y = CL-XX*(SL-SS)/WDTH
    IF (YY .LT. Y) GO TO 56
    IF (RL .GE. CL) GO TO 100
    GO TO 21
 56 IRS = 2
    CCL = CS + (SL-SS)*(WDTH-XX)/WDTH
    CCS = CS
    BASE = WDTH-XX
    DG = DIAG*(WDTH-XX)/WDTH
    GO TO 12
```

```
   57 BASE = XX
      DG = DIAG - DG
      CCS = CCL
      CCL = CL
      GO TO 22
C
C    CALCULATE FINAL AREA AND BURNING EDGES
   99 D = DIAG
      IF (CS .LE. 0.0) D = DIAG*CL/(SL-SS)
      SLAT = D-OSBURN-OLBURN
      BASE = WDTH
      IF (CS .LE. 0.0) BASE = WDTH*CL/(SL-SS)
      AREA = 0.5*BASE*(CL+CS) - PSAREA - PLAREA
      SP = PSBURN + PLBURN
      B = AREA / (0.5*WDTH*(SD1+SD2))
  100 RETURN
C
      END
      SUBROUTINE GENISL(S,A,PRFD,E,ARCP,BCRIT,NTH,INFLG)
C*    *GENISL*      ***      007      ***      11-OCT-83
C*
C*    FINDS SURFACE AREA-CONTRIBUTIONS DUE TO INNER SLIVERS
C*    FOR A MULTIPERFORATED PROPELLANT GRAIN
C*
      IMPLICIT INTEGER (I-N)
      COMMON /CONBLK/
     $ PI,PI2,PI3,PI4,RT3

      DIMENSION S(3),A(4)
C
      IF(INFLG.GT.0) GOTO 20
      A(1)=ACOS((S(2)**2+S(3)**2-S(1)**2)/(2.0*S(2)*S(3)))
      A(2)=ACOS((S(1)**2+S(3)**2-S(2)**2)/(2.0*S(1)*S(3)))
      A(3)=ACOS((S(1)**2+S(2)**2-S(3)**2)/(2.0*S(1)*S(2)))
      A(4)=0.5*S(1)*S(3)*SIN(A(2))
C
      J=0
      DO 15 I=1,3
      IF(A(I).LT.PI4) J=J+1
   15 CONTINUE
C
      IF(J.LE.1) GOTO 30
      NABORT=21
C      CALL PAGCHK(0)
      WRITE(*,1000) PAGC,NABORT,NTH
      GOTO 30
C
   20 TAU12=ACOS(AMIN1(1.0,S(3)/PRFD))
      TAU13=ACOS(AMIN1(1.0,S(2)/PRFD))
      TAU23=ACOS(AMIN1(1.0,S(1)/PRFD))
C
      E=0.0
      ARCP=0.0
      BCRIT=S(2)/SIN(A(2))-PRFD
      IF(TAU12+TAU13+TAU23.GE.PI2) GOTO 30
C
      E=A(4)-0.25*PRFD*(S(1)*SIN(TAU23)+S(2)*SIN(TAU13)
```

```
     $ +S(3)*SIN(TAU12)+PRFD*(PI2-TAU12-TAU13-TAU23))
      E=2.0*E
      ARCP=PRFD*(PI2-TAU12-TAU13-TAU23)
C
   30 RETURN
C
 1000 FORMAT(A1,16H *GENISL* ERROR ,I3,
     $ 31H UNACCEPTABLE GEOMETRY IN GRAIN,I2)
      END
```

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